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DESIGN OPTIMIZATION AND FIELD VERIFICATION OF AN INTEGRATED RESIDENTIAL FURNACE

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ABSTRACT

The report describes part of the second phase of an investigation to further optimize the design of a low-emission/high-efficiency oil-fired residential furnace that was derived from earlier EPA-funded studies and to obtain field verification of its emission and efficiency characteristics. Details concerning three major subdivisions of work in Phase II are given in this report, namely, (1) the construction and installation of the test furnaces, (2) the 1977-79 field test effort, and (3) the analysis of the results of the performance monitoring, including a supplementary laboratory testing effort to evaluate the measurement techniques used in the field test.

CONTENTS

Page

Abstract.... iii

Figures.... v

Tables.... vii

1. Introduction.... 1
2. Conclusions.... 3
3. Recommendations.... 4
4. Field Test Preparation.... 5
   - Description of the Integrated Furnaces.... 5
   - Selection of Host Sites.... 8
   - Field Instrumentation.... 10
5. Field Test Results.... 34
   - Test Objectives.... 34
   - Climatic Condition.... 34
   - Periodic Monitoring.... 35
6. Supplementary Laboratory Tests.... 81
   - Test Objectives.... 81
   - Efficiency Performance Comparison.... 81
   - Pollutant Emissions.... 88
   - Natural Gas Conversion.... 91

References.... 100

Appendices.... 102

A. Field Test Data Acquisition and Reduction Computer Codes.... 102

B. Fuel Oil Composition Analysis Results....

C. Field Test Monitoring - Detail Pollutant Emissions Results....

D. Field Test Cycle-Averaged Gross Thermal Efficiency Data....

E. Linear Regression Analysis Computer Codes, and Results of Cycle-Averaged Efficiency Data Evaluations....

F. Statistical Evaluation of Integrated Furnace Field Test Pollutant Emissions and Efficiency Performance Data....

FIGURES

Page

1. Low-Emission Integrated Furnace Components........................ 6
2. Integrated Furnace Finned Firebox and Heat Exchanger Assembly and Optimum Burner.. 7
3. Photograph of the Woodbine Site Host Dwelling in the Boston Area.. 12
4. Photograph of the Richard Site Host Dwelling in the Boston Area... 13
5. Photograph of the Pond Site Host Dwelling in the Boston Area...... 14
6. Photograph of the Gravon Site Host Dwelling in the Albany Area.... 15
7. Photograph of the Stovepipe Site Host Dwelling in the Albany Area. 16
8. Photograph of the Fissette Site Host Dwelling in the Albany Area.. 17
9. Rockwell International Pollutant Emissions Monitoring Laboratory.. 19
10. Flue Gas Analysis Instrument Module No. 1 Installed in the Mobile Laboratory.. 20
11. Photograph of the Pond Site Installation of the Integrated Furnace with Efficiency Data Logger and Flue Gas Sampling System Attached.. 23
12. Photograph of the H/P System 3051A Programmable Data Logger Used to Monitor Thermal Efficiency of Installed Furnaces.............. 26
13. Schematic of Automatic Field Test Furnace Efficiency Data Acquisition System.. 27
14. Program Logic Schematic for the Cycle-Averaged Thermal Efficiency Data Logger Controller.. 28
15. Photograph of the I.T.C. 9676 Furnace Cycle Timing Data Logger.... 32
16. Integrated Furnace Performance vs Utilization for Unit 5 Installed at the Woodbine Site in the Boston Area During 1977-1978.. 58
17. Integrated Furnace Performance vs Utilization for Unit 4 Installed at the Richard Site in the Boston Area During 1977-1978.. 59
18. Integrated Furnace Performance vs Utilization for Unit 1 Installed at the Pond Site in the Boston Area During 1977-1978.... 60
19. Integrated Furnace Performance vs Utilization for Unit 2 Installed at the Gravon Site in the Albany Area During 1977-1978.. 61
20. Integrated Furnace Performance vs Utilization for Unit 6 Installed at the Stovepipe Site in the Albany Area During 1977-1978.. 62

FIGURES

Page

21. Integrated Furnace Performance vs Utilization for Unit 3 Installed at the Fissette Site in the Albany Area During 1977-1978 63
22. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 5 Installed at the Woodbine Site in the Boston Area During 1978-1979 65
23. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 4 Installed at the Richard Site in the Boston Area During 1978-1979 66
24. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 1 Installed at the Pond Site in the Boston Area During 1978-1979 67
25. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 2 Installed at the Gravon Site in the Albany Area During 1978-1979 68
26. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 6 Installed at the Stovepipe Site in the Albany Area During 1978-1979 69
27. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 3 Installed at the Fissette Site in the Albany Area During 1978-1979 70
28. Photograph of the Residential Furnace Pollutant Emissions and Efficiency Measurement Laboratory System 83
29. Comparison of Laboratory Test Results with Field Test Results for the Pond and Gravon Site Integrated Furnace Units 86
30. Comparison of Efficiency Performance Before and After Cleaning of the Heat Exchanger Surfaces in the Pond and Gravon Integrated Furnace Units 87
31. Comparison of Measured Output Efficiency Laboratory Results Between the Pond and Gravon Furnaces in Cleaned Condition 89
32. Comparison of Efficiency Performance of Oil-Fired and Natural Gas-Fired Integrated Furnace Configurations 98

TABLES

Page

1. Estimated Cost of Manufacturing Special Components for the Integrated Low-Emission Residential Warm-Air Furnace............. 9
2. Description of the Host Dwellings Selected for Field Test of the Integrated Furnace....................................... 11
3. Flue Gas Emissions Mobile Laboratory Instrumentation............. 21
4. 1977-1978 Integrated Furnace Field Test Cycle-Averaged Pollutant Emissions Summary for the Boston-Area Installations..... 37
5. 1977-1978 Integrated Furnace Field Test Cycle-Averaged Pollutant Emissions Summary for the Albany-Area Installations..... 42
6. 1978-1979 Integrated Furnace Field Test Cycle-Averaged Pollutant Emissions Summary for the Boston-Area Installations..... 44
7. 1978-1979 Integrated Furnace Field Test Cycle-Averaged Pollutant Emissions Summary for the Albany-Area Installations..... 46
8. Summary of 1977-1978 Heating Season Pollutant Emissions Averages from the Integrated Furnace Systems..................... 48
9. Summary of the 1978-1979 Integrated Furnace Field Tests Pollutant Emissions Averages.................................. 50
10. Tabulation of Integrated Furnace Short-Term Average Thermal Efficiency Performance During the 1977-1978 Heating Season........ 53
11. Results of the Single-Parameter Linear Regression Analysis of Cycle-Averaged Efficiency Data Obtained from the Integrated Furnace Units in the 1977-1978 Field Test........................ 56
12. Comparison of Curve-fit Correlation Coefficients Generated from Least-Squares Regression Analysis on the Field Test Output Efficiency Data.. 72
13. Summary of Estimated Season-Averaged Thermal Efficiency Performance of the Integrated Furnaces............................ 74
14. Effect of Integrated Furnace on Fuel Oil Consumption............. 76
15. Results of the NBS Furnace Rating Procedure for the Pond and Gravon Field Installations..................................... 79
16. Comparison of the Results of the NBS Furnace Rating Procedure for the Pond and Gravon Furnaces in the Field and in the Laboratory... 84
17. Cycle-Averaged Pollutant Emissions Concentrations from the Pond and Gravon Integrated Furnaces Tested in the Laboratory...... 90

TABLES

Page

18. Pollutant Emission Concentrations from the Integrated Furnace Fired by a Natural Gas Conversion Burner........................ 92
19. Pollutant Emission Concentrations from the Natural Gas-Fired Integrated Furnace with a 0.30-m Diam Insulator Installed in the Firebox.. 93
20. Pollutant Emission Concentrations from the Natural Gas-Fired Integrated Furnace with a 0.22-m Diam Insulator Installed in the Firebox.. 94
21. Comparison of the Results of the NBS Furnace Rating Procedure for the Gravon Furnace Fired with No. 2 Fuel Oil and with Natural Gas.. 97

SECTION 1

INTRODUCTION

The design optimization and field verification of an integrated residential furnace effort consisted of two phases. Phase I, the design optimization and field test preparatory phase, has been accomplished and is described in detail in Reference 1. Phase II, the field test verification of the resultant low-NO$_x$ furnace design, is described in this report.

The Phase I furnace design optimization work was a culmination of prior research studies of oil burner flames and firebox effects for reducing oxides of nitrogen emissions from which low-NO$_x$ design guidelines were developed and applied to a candidate warm-air furnace design. The Phase I effort reexamined the candidate low-NO$_x$ design, refined component modifications to be amenable to production line-type manufacturing methods, and laboratory tested the new components. In the laboratory tests, pollutant emissions performance of the newly designed components was measured and their durability evaluated in preparation for field test application. A prototype of the integrated furnace was then submitted to Underwriters' Laboratories for their evaluation of the safety of the design, while hot-fire testing along the UL 727 specifications was conducted in-house to assure safe operation in the field.

The field test preparations in Phase I included selection of test cities, securing heating service support, and preliminary selection of specific host dwellings for six field test integrated furnace units. The selection of candidate cities was initiated with a review of available climatological and census data. Boston, Massachusetts, and Albany, New York, were the areas selected; both have high oil usage for heating and very cold winters, and their climates are influenced by different factors, maritime and continental, respectively. Local heating service contractors were engaged as subcontractors to provide:

1) Candidate dwellings for host sites
2) Installation of the test furnaces
3) Service during the field test period
4) Post-test site restoration
5) Supplementary information and comments.

The objectives of the Phase II 1977-78 winter season were to subject six furnaces of the optimized design, which integrated both low-emission and high- efficiency considerations, to real conditions encountered in the field and to monitor the emissions and the efficiency performance through a complete heating season. This involved the construction of six integrated furnace units, selection of host dwellings, and preparation of monitoring equipment before the actual field testing task. Performance goals were set at near-laboratory achievable levels. These goals were to achieve: (1) a 65% reduction in nitric oxide (NO) emissions compared to an average of existing furnaces (Reference 2), while maintaining control of the carbonaceous pollutants (CO, UHC, and smoke); and (2) a 10-percentage-points average increase in installed, gross thermal efficiency over the existing heating units in the host dwellings. The field test monitoring equipment included a fully equipped, mobile, flue-gas analysis laboratory scheduled for pollutant emissions measurements on all six test furnaces on a monthly basis. Efficiency performance was continuously monitored by two types of automatic data loggers, the primary type acquiring detail information of heat flow through the furnace along with firing cycle timing data, and the secondary type supporting the basic data with firing cycle timing information on the remaining five test furnaces. The primary data logger system was rotated to all installations during the heating season to obtain efficiency characterizations for each furnace.

The Phase II effort was extended to: (1) continue field testing through a second heating season (1978-79) to expand the data base and (2) test two of the field test furnaces under laboratory conditions to provide comparative data on the field test monitoring method and the NBS specified furnace rating procedure. This Phase II Final Report describes the 1977-79 field and laboratory testing activities and the results.

SECTION 2

CONCLUSIONS

Based on the experience and results obtained from the field testing of six integrated furnaces during the 1977-78 and 1978-79 heating seasons, it can be concluded that:

1) The low-emission design criteria developed in preceding laboratory studies (Contracts 68-02-0017 and 68-02-1819) can be extended to designs amenable to commercial production.

2) A 65% reduction of NO emissions can be achieved and sustained in the field while maintaining control of carbonaceous pollutants.

3) Cycle averaged efficiencies on the order of 70 to 80% were achieved in conjunction with reduction of pollution emissions, which resulted in improvements in fuel utilization of 10 to 20%.

4) Fuel bound nitrogen content of the fuel oil may vary significantly and directly affect the flue gas NO emission concentrations.

5) Contaminants in the fuel oil significantly affect the long-term smoke emissions performance of the furnace, and future furnace systems should include considerations for better oil filter/trap assemblies.

6) Incorporation of a positive flue pipe/sealed air intake closure device instead of an inlet closure device would further improve cycle averaged efficiency at low furnace utilization levels and reduce the likelihood of corrosion in the flue pipe.

7) The design is amenable to natural gas-fired conversion with only minor modification to the cooling characteristics of the finned firebox.

8) The DOE/NBS method for determining the seasonal performance of residential furnaces (NBSIR 78-1543) tends to produce significantly higher cyclical and steady-state efficiency values than those measured by the EPA/Rockwell method developed during this program. This is the result of assumptions concerning heat losses which are incorporated into the DOE/NBS method, causing higher estimated seasonal cyclic efficiency performance than the steady-state mode, an unrealistic situation.

SECTION 3

RECOMMENDATIONS

The full value of the low-emission/high-efficiency furnace technology may be realized only by widespread commercial application. In view of the results and conclusions of the Phase II field verification effort during the 1977-78 and 1978-79 heating seasons and the supplementary laboratory testing effort, it is recommended that:

1) The integrated furnace technology be instituted into commercial furnace manufacturing.

2) More information be made available to the ultimate consumer and the homeowner on the available furnace technology to prompt market demand for more efficient, low-polluting devices.

SECTION 4

FIELD TEST PREPARATION

DESCRIPTION OF THE INTEGRATED FURNACES

The effort in the first phase of this contract (Reference 1) was to finalize a configuration that incorporated both low-emissions design criteria and fuel-conserving techniques into a viable, commercially producible furnace unit. Six furnaces of this configuration were then constructed for field testing early in the Phase II effort.

The most expedient way of constructing only six furnaces was to purchase commercially available units and institute the desired modifications. The Lennox Industries Model 011-140 furnace was selected as the foundation for the modifications because of its compact heat exchanger and outside dimensions. Figure 1 is a line drawing of the integrated furnace configuration surrounded by photographs of the modified components. Most component modifications were minor refinements of the laboratory prototypes to improve producibility. The finned firebox, however, received major refinements for the field test configuration, changing from welded-steel fabrication to cast-iron for potential mass producibility. The fin heights and placements were changed for better temperature distribution to reduce internal stresses, thereby increasing potential service life. A carbon-steel ring integrally attached into the top of the cast firebox facilitated mating of the stock, carbon-steel heat exchanger by conventional welding.

Baffles were added along the side walls (see Figure 2) to assure air flow along the finned firebox. These baffles continue up alongside the heat exchanger panels to reduce bypass flow. The firebox and heat exchanger compartment is insulated on all sidewalls with 1-in. "Cerafelt" (mineral wool) insulation, reducing cabinet heat losses to near zero.

The burner, also shown in Figure 2, incorporates an optimized head, a quiet stator, an oversized static disc, and a standby draft control assembly with integral microswitch safety circuitry. The burner head is a nonretention type, using the plug-flow, low-emissions design criteria and fabricated from 22-gauge, Type 310 stainless steel sheet stock. To reduce feed-system induced pulsations, a quiet stator on the blower and an oversized static disc in the blast tube are incorporated in the optimum burner. The draft control assembly serves a twofold purpose of reducing standby heat losses by convection and maintaining the temperature of the firebox for a cleaner start on the next firing.

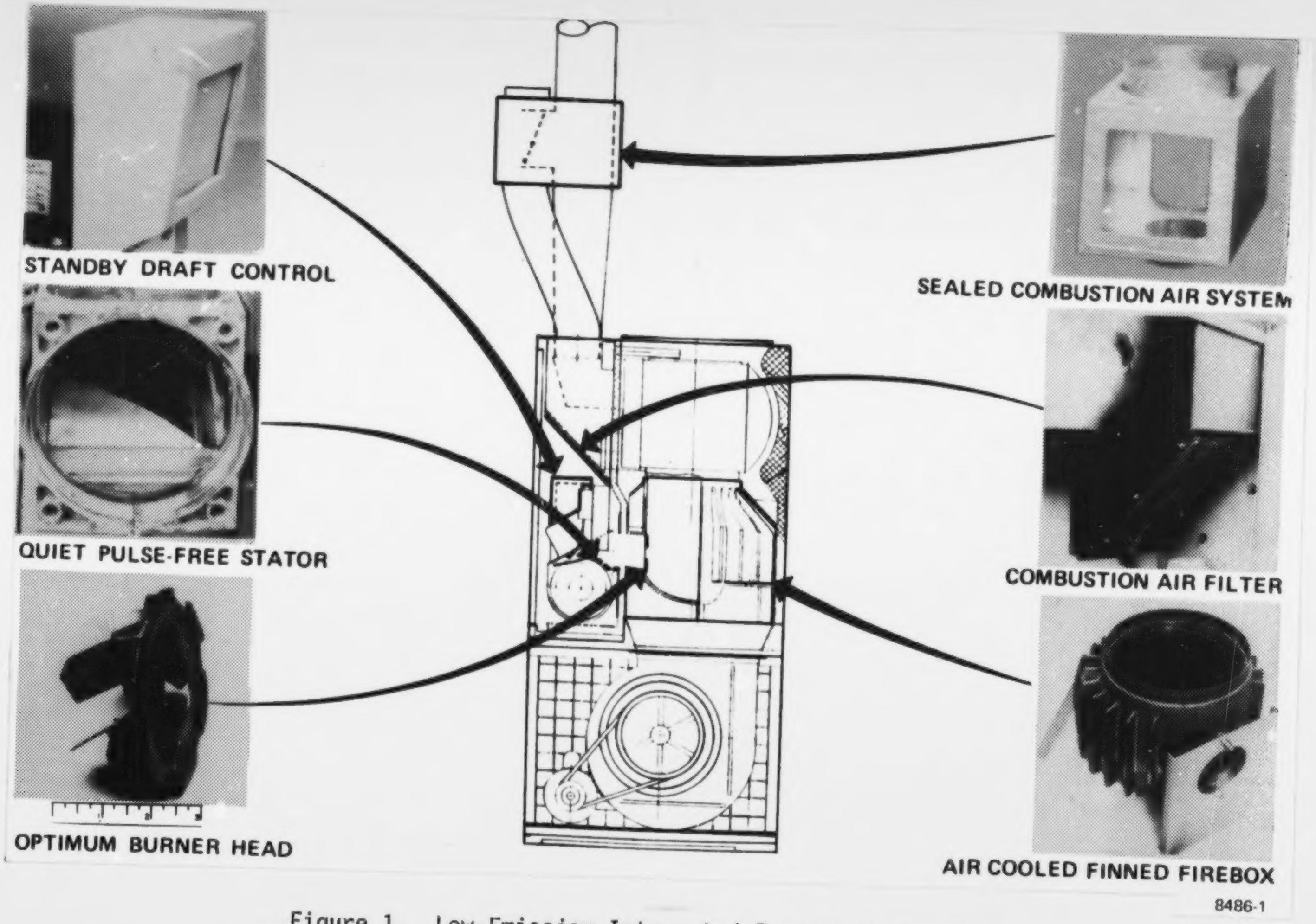

STANDBY DRAFT CONTROL
QUIET PULSE-FREE STATOR
OPTIMUM BURNER HEAD
SEALED COMBUSTION AIR SYSTEM
COMBUSTION AIR FILTER
AIR COOLED FINNED FIREBOX
8486-1

Figure 1. Low-Emission Integrated Furnace Components

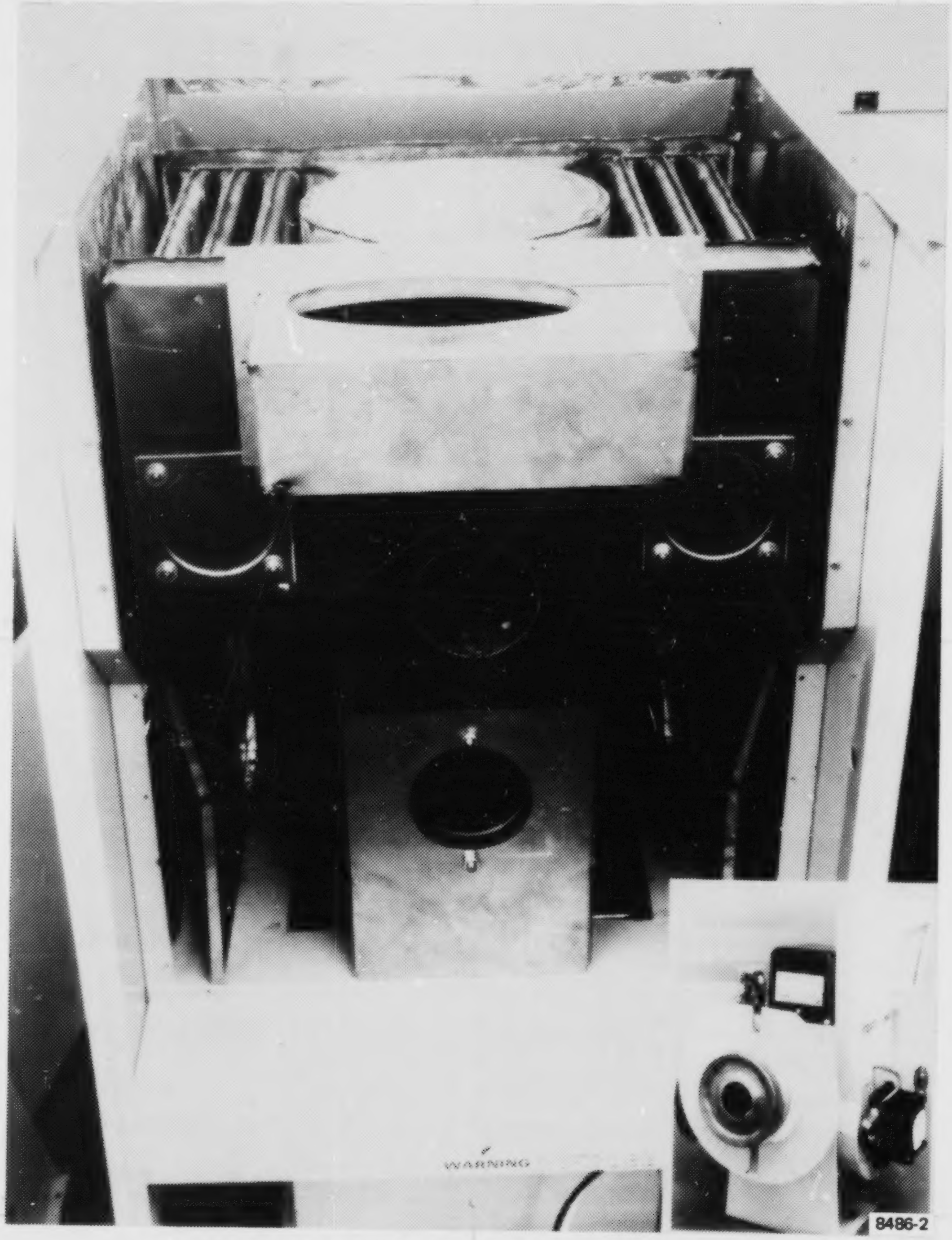

WARNING
8486-2

Figure 2. Integrated Furnace Finned Firebox and Heat Exchanger Assembly and Optimum Burner

The integrated furnace system is completed with a "sealed-air" subsystem, which transports outside air to the burner and the flue damper. This reduces dwelling heat losses through the burner and damper. The subsystem consists of 0.18-m (7-in.) diameter insulated ducting from an opening to the outside, to a plenum around the flue damper, and continuing on with 0.10-m (4-in.) diameter ducting to the top of the burner vestibule. Immediately under the entry to the vestibule is a filter box to assure consistent burner blower characteristics, which are important in the near-stoichiometric design operating conditions. The louvers in the vestibule cover are closed over by sheet metal, thereby "sealing" this air system from that of the dwelling.

The additional cost of a production line version of the integrated furnace system is estimated to be $79.65 (1976 prices, see Table 1). The cooled firebox and optimum burner head replace components that would normally be included in a conventional furnace; thus, the net costs are also presented in Table 1 and were used in the estimate of additional cost. The conventional firebox is typically of sheet steel with "fiberfrax" insulative liner or of stainless steel construction. The cost of fabricating a conventional firebox was estimated to be approximately $15.00, which was applied in the calculation of net cost. The method selected for fabrication of the optimum burner head involves an additional folding operation over conventional stamped-construction heads that accounts for the slightly higher ($0.75) estimated net cost of manufacturing. Installation of the furnace system requires additional effort to complete the plumbing of the sealed-air system, estimated by the installers of the field test systems to be approximately $100+, depending upon the configuration of each site. Details of the design of the modified components are described in Reference 1. The complete integrated system is approximately 75 lb heavier than the original Lennox 011-140, primarily because of the intentionally massive heat-retaining firebox. The added weight adds approximately $3 to a 1,000-mile freight delivery. United States Patent 4,138,986 was issued in 1979 covering the furnace design features previously discussed. It is assigned to the U.S. Environmental Protection Agency.

SELECTION OF HOST SITES

Three field test units were located in each of two test locales where oil heat is used in a substantial fraction of single-family homes and which have distinctly different winter climates (Reference 1). The cities selected for the field test were Boston, Massachusetts, and Albany, New York. Boston's Atlantic shoreline location provides a maritime climate, and the Appalachian mountain range isolates Albany, New York, to a continental climate. Both cities were visited by Rockwell personnel, the field test plan was presented to several heating service contractors, and commitments were established with two of the contractors, one in each city. The contractor retained for support of the Boston area test is involved in furnace sales, installation, and service. The Albany, New York, contractor provides the same services, but in addition also is involved with fuel oil sales and delivery.

A list of potential host dwellings was supplied by each of the two service contractors from their existing customer lists. The selection of the six host sites (single-family dwellings) was based on criteria that included consideration of (1) dwelling construction, (2) dwelling location, (3) dwelling existing

TABLE 1

ESTIMATED COST OF MANUFACTURING SPECIAL COMPONENTS FOR THE INTEGRATED LOW-EMISSION RESIDENTIAL WARM-AIR FURNACE

Integrated Furnace Component	Material	Estimated Manufacturing Cost, $*	Remarks
Firebox	Cast Iron	51.40 (36.40)	Vendor Bid
Burner Head	310 SS	1.75 (0.75)	Vendor Bid
Warm-Air Baffles	Steel	2.50	Engineering Est.
Draft Flap Plenum And Safety Switch	Steel Microswitch	11.50	Engineering Est.
Quiet Stator	Steel	.50	Engineering Est.
Cabinet Insulation	Rock Wool	4.00	Engineering Est.
Sealed-Air System			
Flue Plenum	Steel	10.00	Engineering Est.
Vestibule Filter	Steel/Fib. Gl.	4.00	Engineering Est.
Insul. Ducting	Aluminum	10.00	Engineering Est.
Installation	--	100.00+	Heating Service Est.

*1976 prices, 10,000 units/yr production rate. Partially assembled, production line ready

()Net additional cost

furnace installation, (4) fuel usage history, and (5) host family. A variety of types of dwelling construction, age, insulation, and architecture was sought. The topography of the sites was also considered; houses near large bodies of water or hills may be influenced by the heat storage capacities of these masses, and dense tree surroundings reduce insolation, convection, and radiation. A variety of existing furnaces was also sought to provide a more comprehensive sample for comparison.

The final selection resulted in six dwellings of a variety of characteristics that are listed in Table 2 and shown photographically in Figures 3 through 8. The dwellings range from 14 to 80 years of age, one to five occupants, and fuel utilization K-factors of 3.52 to 11.48 degree-day per gallon of fuel. These average fuel utilization factors are based on the fuel consumption and climatological histories of the prior two heating seasons. The three homes chosen in the Boston area offer a broad range of house characteristics: an approximately 80-year-old three-story Victorian (Woodbine St.), a 21-year-old split-level ranch (Richard Road), and a 32-year-old two-story Cape Cod (Pond Ave.). They all have refrigerated air conditioning and each is occupied by only two adult residents. Because of the colder design temperature in Albany than in Boston and the moderately low firing rate of the test furnaces, there is less range in house types among the three in Albany, but there is a greater variation among the occupants. All three are small (on the order of 1000 ft^2 in the main floor) single-story structures with full basements and no air conditioning. One is half of a nearly-separated (common garage) 20-year-old duplex occupied by a single person (Gravon Drive). The other two are single-family houses. One is a 30-year-old rectangular ranch style occupied by a family of four with two children in their upper teens (Stovepipe Road). The other is a 25-year-old, essentially square house occupied by a family of five, including two daughters approximately 8 and 13 and a son approximately 18 years old (Fissette Drive). All of the dwellings, with the exception of Woodbine, have insulation or insulative design incorporated in the wall surfaces. The Woodbine dwelling has no insulation and the greatest exposed wall surface, and the effect on fuel utilization is very obvious in Table 2. All host dwellings have been firing No. 2 fuel oil at 0.79 ml/s (0.75 gph), which is design throughput for the installed integrated furnace.

The existing furnaces being replaced for the field test represent a wide spectrum, from a 20-year-old unit representing furnaces near the end of their service life to a 3-1/2 and a 5-year-old Lennox 011-140 representing the most modern-design, commercially available furnace. The Lennox 011-140 is also the foundation of the integrated furnace body and was selected because of its compact design.

FIELD INSTRUMENTATION

Monitoring of the pollutant emissions is the primary scientific objective of the field test; however, the effect of pollution reduction devices on fuel utilization is also of great concern in these times of energy shortages. Therefore, the field test instrumentation consisted of two sets of equipment with different monitoring techniques, each set dedicated to one of the two areas of concern. The pollutant emissions measurement equipment consisted of

TABLE 2

DESCRIPTION OF THE HOST DWELLINGS SELECTED FOR FIELD TEST OF THE INTEGRATED FURNACE

Test Site	Number of Occupants	Type of Architecture	Type of Wall Construction	Levels of Living Space	Age of Structure (Years)	Age of Furnace (Years)	Prior Average K-Factor (Degree-Day*/gal)
Woodbine Street Newton, MA	2	Wood Frame	Wood	3	80	5	3.52
Richard Road Needham, MA	2	Split Level	Wood	1-1/2	21	21	7.84
Pond Avenue Brookline, MA	3	Colonial	Wood	2	32	3-1/2	8.04
Gravon Drive Delmar, NY	1	Duplex	Brick/Wood	1	20	20	10.92
Stovepipe Road Clarksville, NY	4	Ranch	Sheet Rock	1	14	14	10.49
Fissette Drive Feura Bush, NY	5	Wood Frame	Sheet Rock	1	25	5	11.48

*Degree-Day: Boston = 65°F Ref., Albany = 70°F Ref.

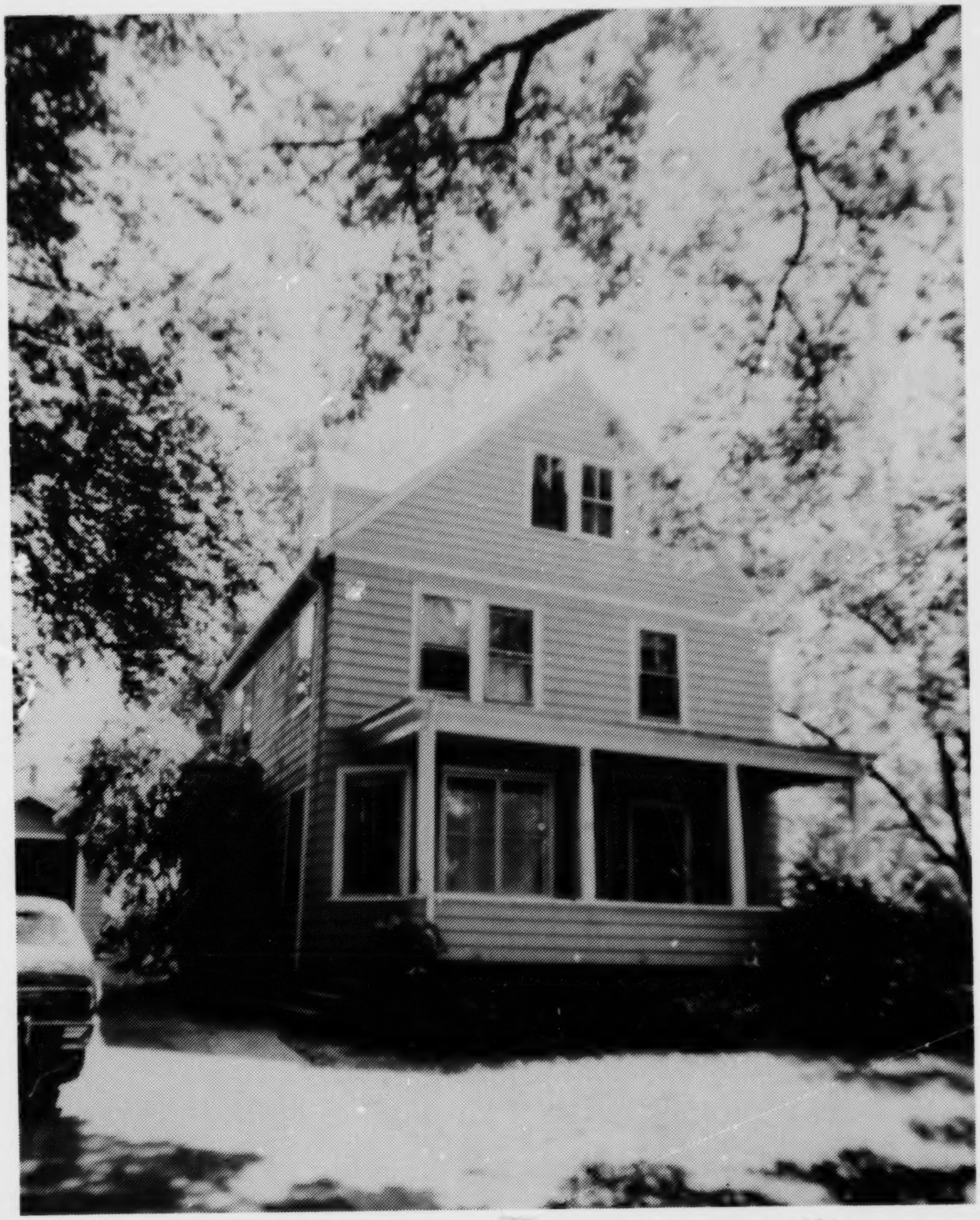


Figure 3. Photograph of the Woodbine Site Host Dwelling in the Boston Area

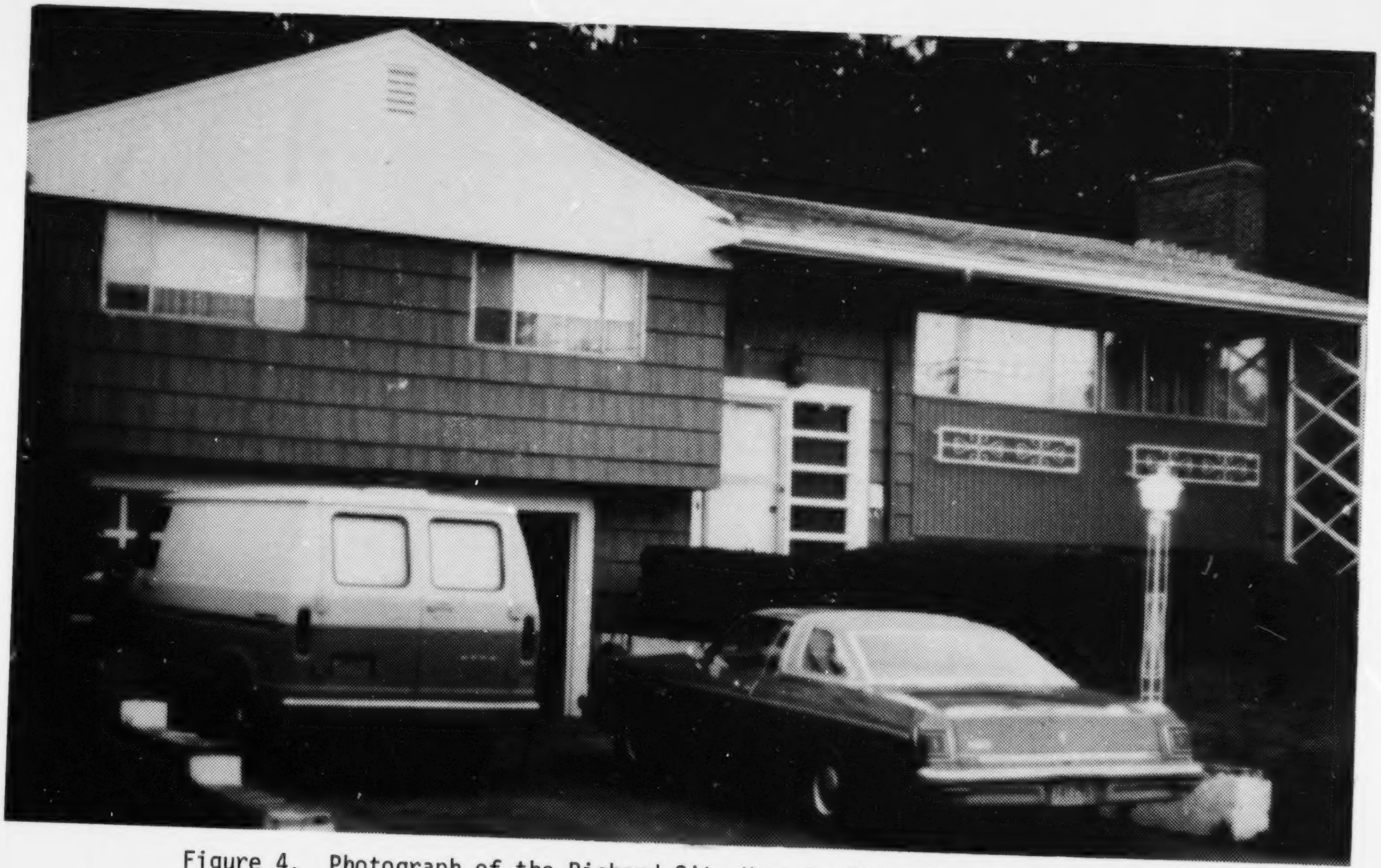


Figure 4. Photograph of the Richard Site Host Dwelling in the Boston Area

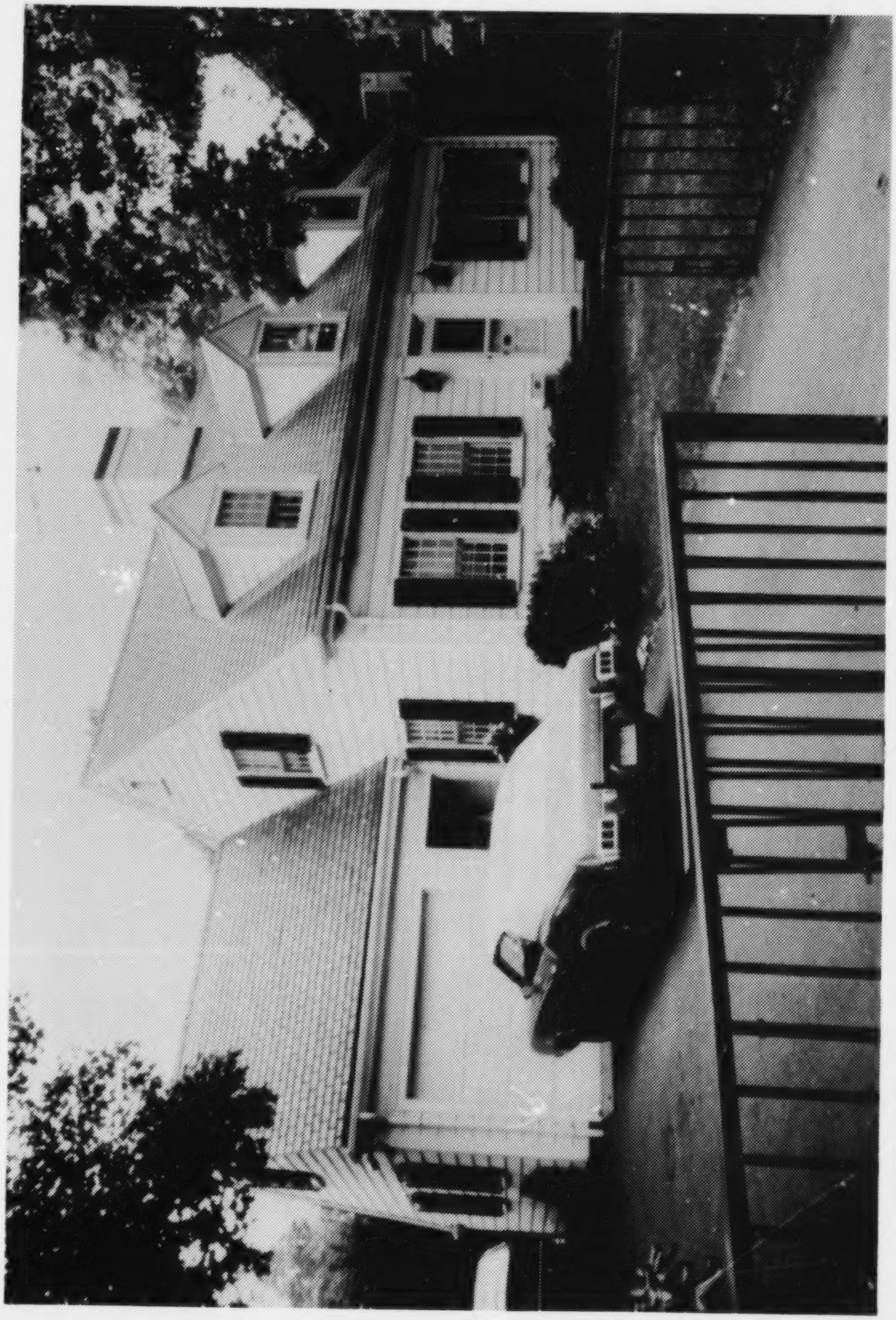


Figure 5. Photograph of the Pond Site Host Dwelling in the Boston Area

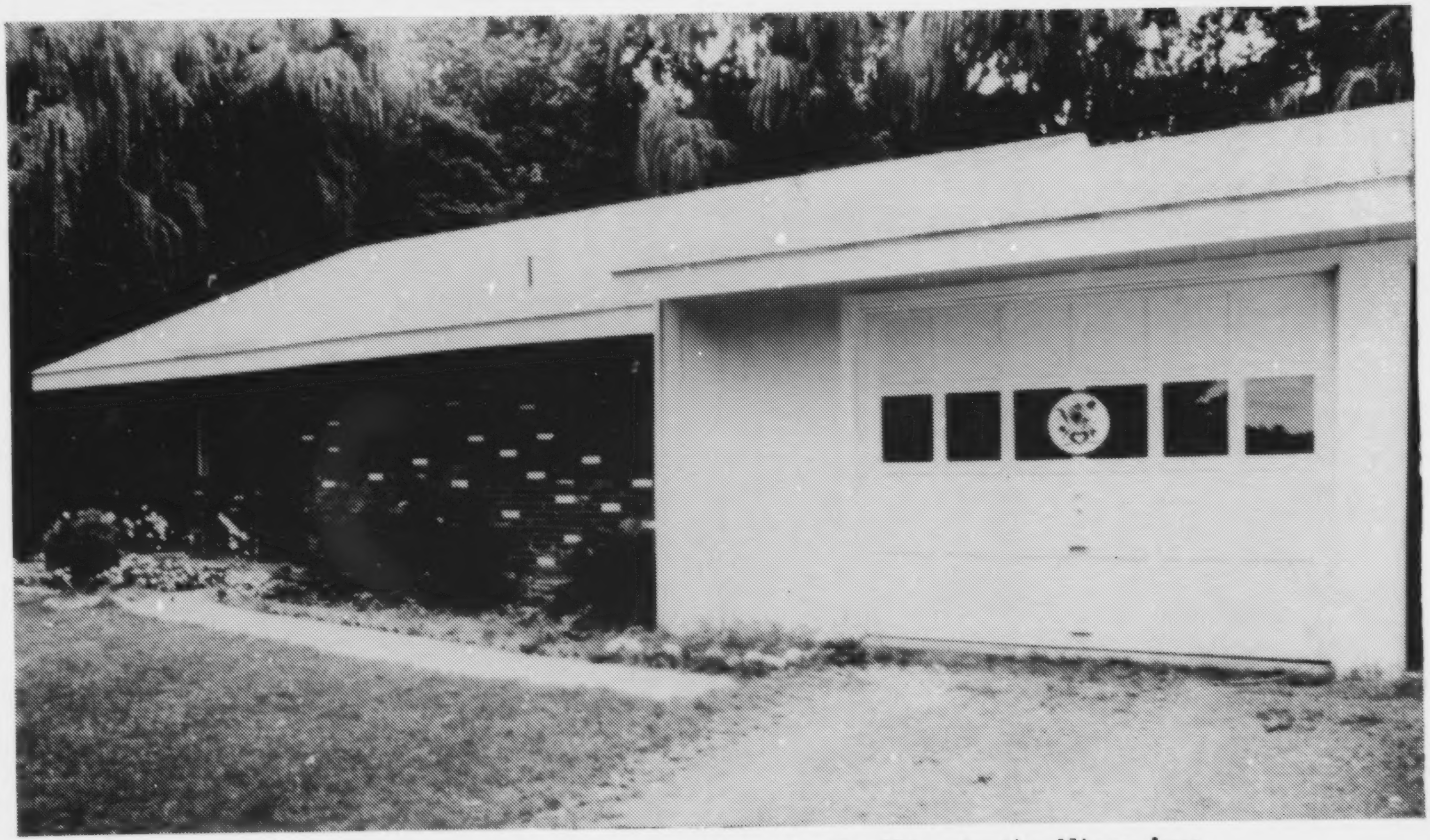


Figure 6. Photograph of the Gravon Site Host Dwelling in the Albany Area

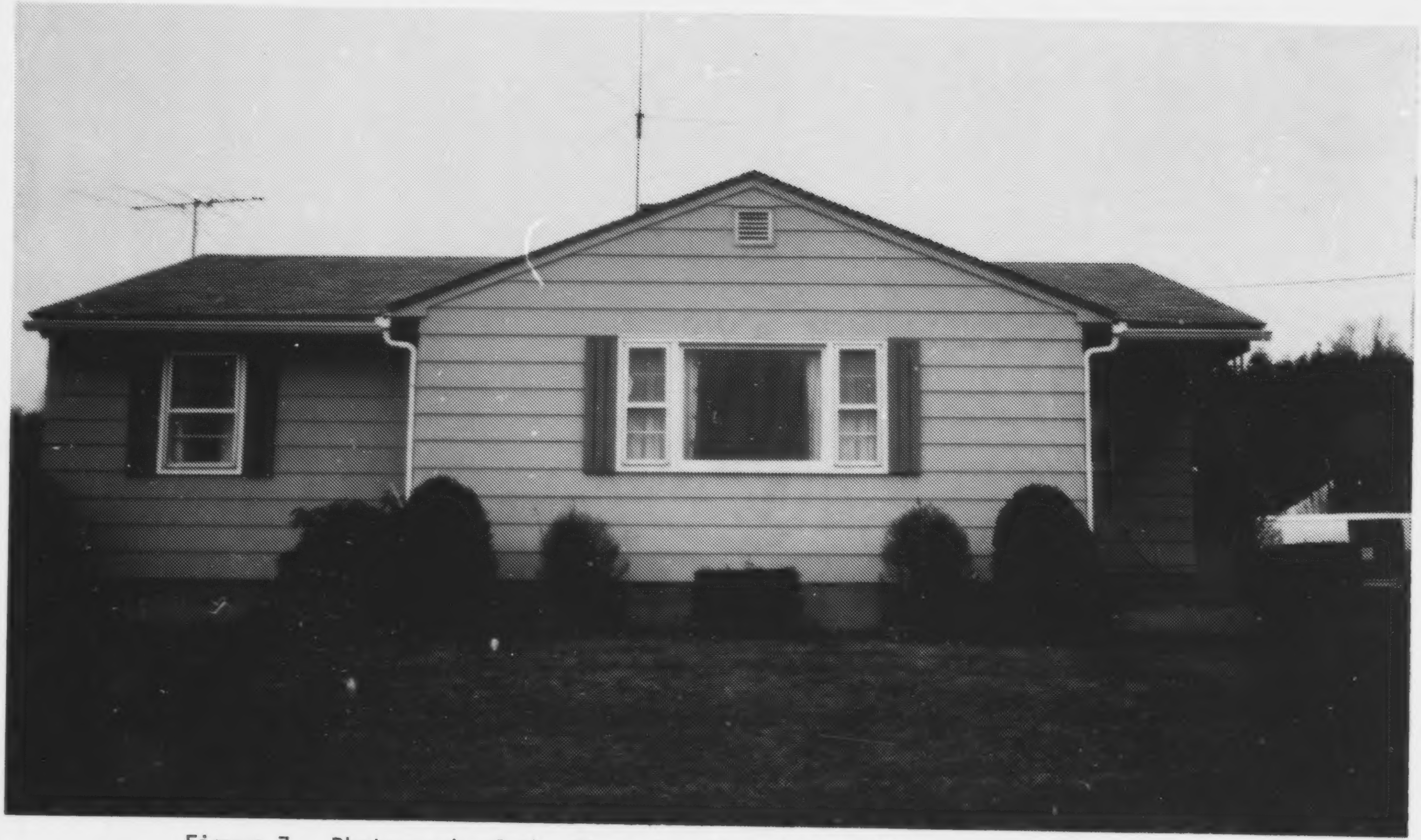


Figure 7. Photograph of the Stovepipe Site Host Dwelling in the Albany Area

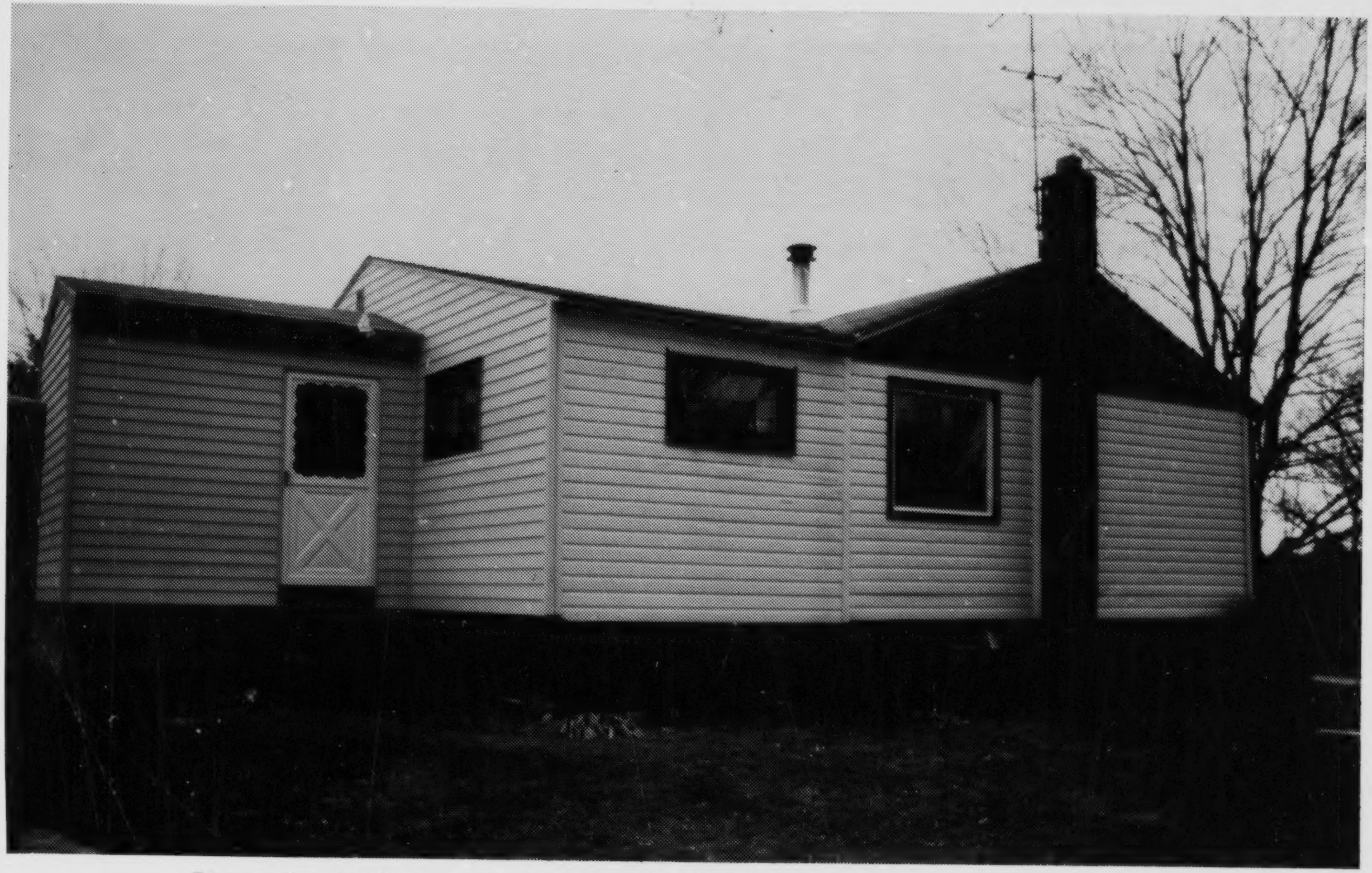


Figure 8. Photograph of the Fissette Site Host Dwelling in the Albany Area

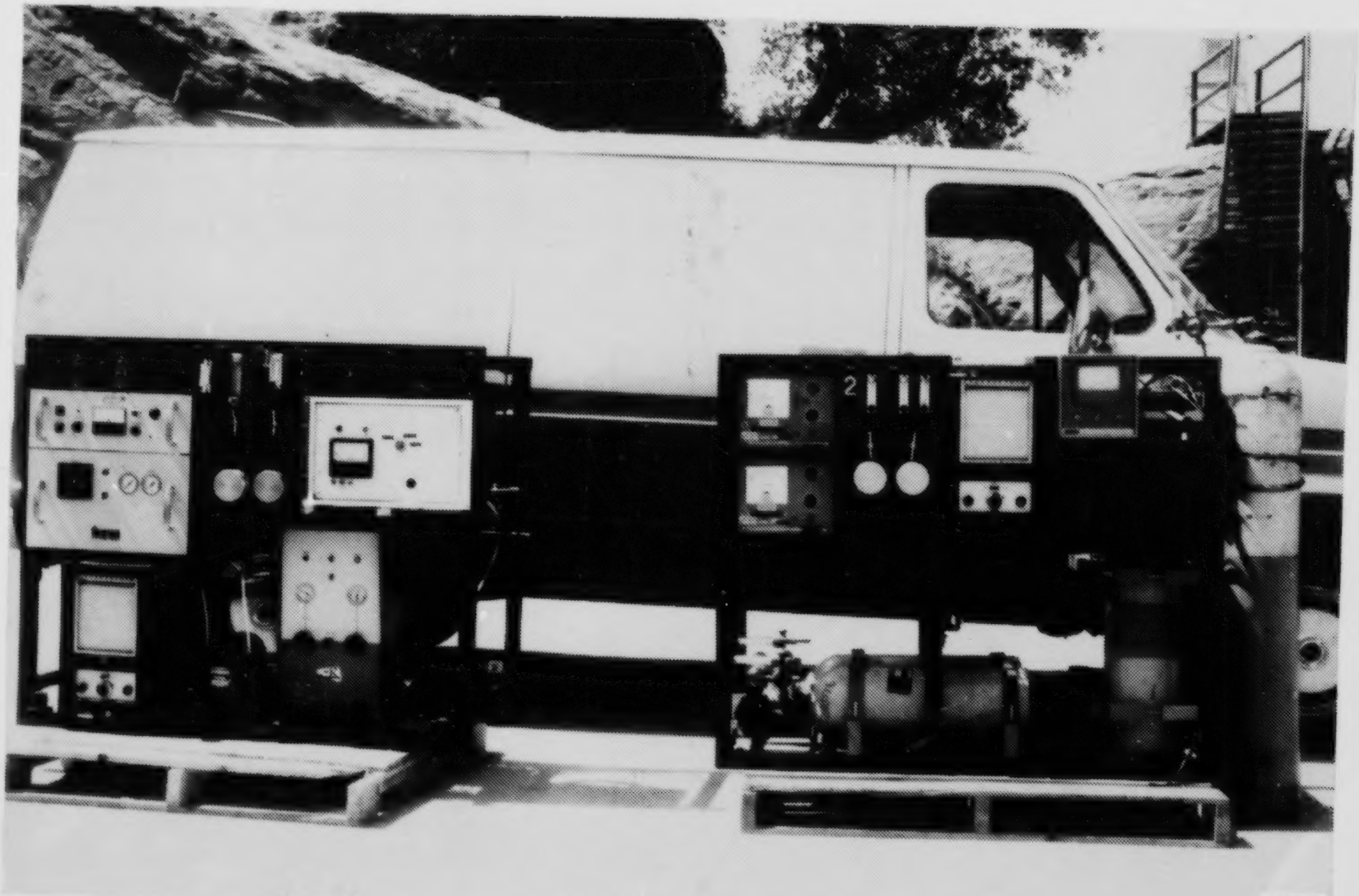
a number of gas analyzers, assembled into a mobile unit and transported to each site on a periodic basis. The thermal efficiency measurement equipment consisted of one programmable data logger system and five supplementary firing cycle time recorders, all operating on a continuous monitoring basis.

Emissions Monitoring Mobile Laboratory

The pollutants of concern are oxides of nitrogen (NO_x), carbon monoxide (CO), unburned hydrocarbons (UHC), and smoke. Carbon dioxide (CO_2) and oxygen (O_2) are components also measured to accurately establish the burner operating conditions. The instruments to measure these gas components at flue gas concentrations were from the consoles used in in the Rockwell furnace laboratory, and therefore the data reduction procedure remained unchanged. The instruments were remounted, along with the required supplementary systems, into two rack assemblies designed to fit into the freight bay of a 3/4-ton Ford van. The two assembled instrumentation modules are shown in Figure 9 alongside the carrier vehicle. Visible on the modules are the primary instruments, strip chart recorders, hydrogen generator, calibration gas cylinders, sample pumps, gas valves, and flowmeters. Figure 10 shows Instrument Module 1 installed in the vehicle on rubber vibration isolation mounts, six of which are visible in the photograph along the bottom of the module. The enclosed bay of the vehicle is completely insulated with fire-retardant "ethafoam" for the winter duty. The white surface of the foam slabs appears as the floor of the van in this photo. Table 3 lists the capabilities of the instruments in the emissions-monitoring mobile laboratory along with the methods used for analyses. Although the chemiluminescent NO analyzer is equipped with a NO_2-to-NO converter allowing it to measure NO_x ($NO + NO_2$), no attempt has been made thus far to measure the NO_2 component in the field because of the requirement for a condensation-free (heated) sample transport line. Assembly of a heated sampling line system is planned, and the NO_2 concentration will be checked in the field to confirm previous laboratory readings which indicated the NO_2 emission component to be a factor of 9 less than the NO emissions (volumetric concentration comparisons), or approximately 15% by weight of the total NO_x.

The CO and CO_2 analyzers use the method of absorption of infrared energy, and they require well-stabilized cell operating conditions. To minimize destabilizing interruptions in electrical power to these instruments, the mobile laboratory has two 120 V ac power systems. The primary system consists of two passive, external power supply circuits with provisions for connection to the dwelling's 120 V ac power circuit. This, of course, provides only for the stationary mode of operation. To keep the infrared cells stabilized by operating continuously, a 12 V dc to 120 V ac power inverter provides a secondary source of electrical power for the in-transit mode. The result of having this primary-secondary electrical system has been reliable performance from the CO and CO_2 analyzers through 10 months of varying ambient conditions and 8000 miles of travel duty (i.e., vibration).

The flue gas sampling train consists of several elements that condition and transport the gas from the basement furnace installation to the instruments in the van, which is located typically about 25 m (80 ft) away. The sample is



8486-3

Figure 9. Rockwell International Pollutant Emissions Monitoring Laboratory

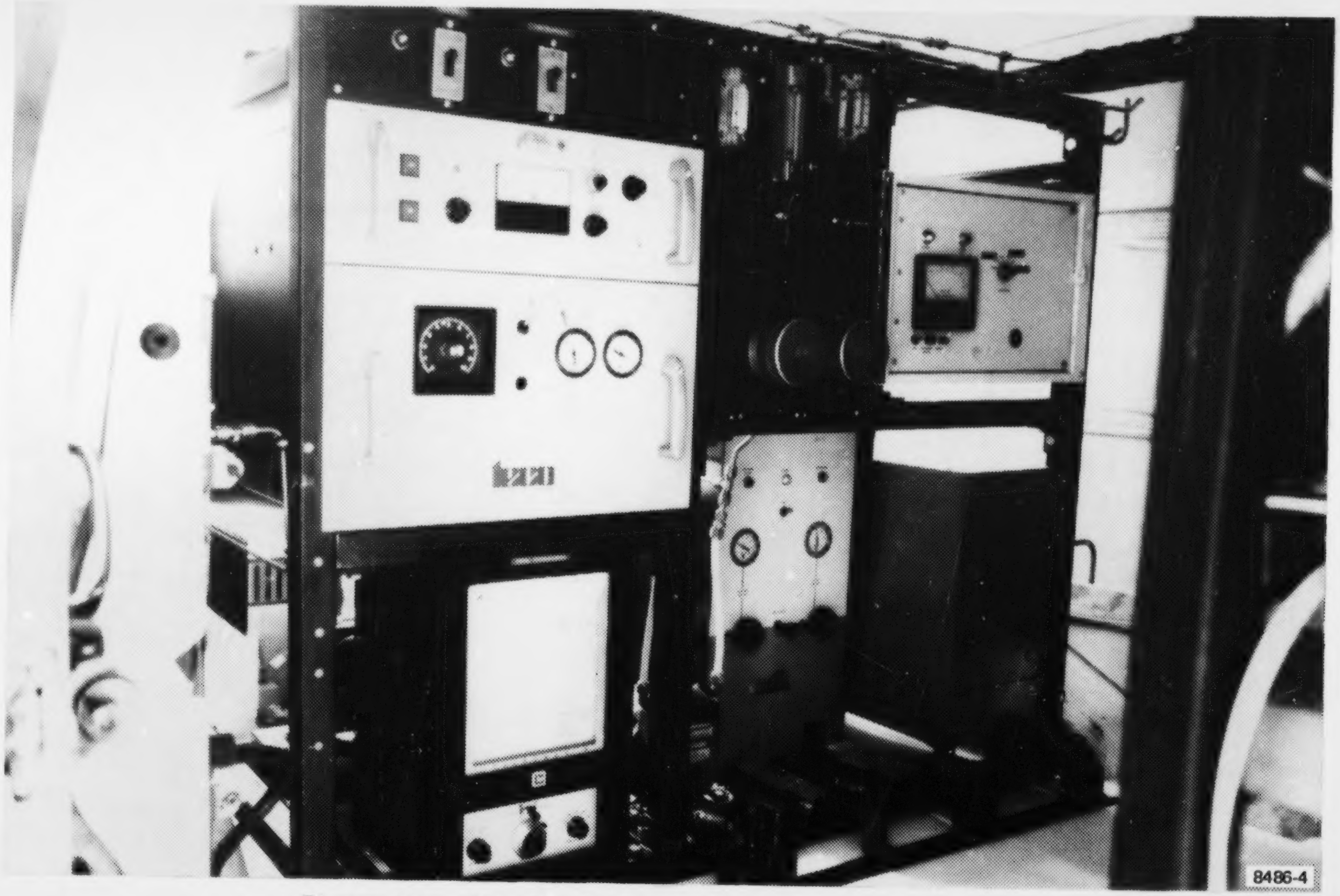


Figure 10. Flue Gas Analysis Instrument Module No. 1 Installed in the Mobile Laboratory

TABLE 3
FLUE GAS EMISSIONS MOBILE LABORATORY INSTRUMENTATION

Species	Range (Resolution)	Instrument Manufacturer and Model	Measurement Method
CO	0 to 1500 ppm (2 ppm)	MSA LIRA 300	Infrared
CO_2	0 to 15% (0.1%)	MSA LIRA 300	Infrared
NO/NO_x*	0 to 1000 ppm (1 ppm)	TECO 10A	Chemiluminescent
O_2	0 to 25% (0.2%)	Beckman	Polarographic
UHC	0 to 3000 ppm (2 ppm)	MSA	H_2 Flame Ionization
Smoke	0 to 9 Bacharach Scale	Bacharach	Hand Pump
Temperature	0 to 500°F (2°F)	—	Mercury Thermometer

*Special heated sampling train required for NO_2 measurement drawn by diaphragm-type suction pumps located within each instrumentation module; the total flow rate required is approximately 1.0 x 10^{-4} m^3/s (13.0 scfh). Figure 11 is a photograph of the Pond installation during the field test monitoring visit with the emission sampling equipment installed. The sample is extracted from the flue by a stainless steel probe and drawn through a stainless steel cooling coil, then down a short length of T.F.E. (Teflon) tubing to an ice-cooled condensibles and particulates trap (seen at the bottom center of the photograph), where nearly all of the condensibles and particulates are removed by the cooling effect and glass-wool filter element. The coil of stainless steel tubing was added to the probe for sampling of gases from the combustion zone, acting as an air-cooled heat exchanger to lower the combustion gas temperature to a tolerable level for the Teflon tubing. The removal of condensibles at this point is important to reduce the likelihood of plugging by freezing of the water when the sample is transported outdoors to the van through a 30-m (100-ft) length of Teflon tubing. The tubing connects to an external fitting on the vehicle, and thereafter the gas sample is carried internally by stainless steel tubing to a second glass-wool particulates filter. The sample path then splits and the portion destined for the infrared analyzers is dried further by passage through a desiccant ($CaSO_4$) column before being admitted to the infrared instruments to eliminate measurement errors induced by the presence of infrared-absorbing water vapor. The second gas sample path leads directly to the NO/NO_x and the UHC analyzers, avoiding any chemical desiccants that may influence the analyses. Calibration gases, of the appropriate species and concentrations (N_2 diluent), and zero gas (N_2) are available to each instrument through four-way gas valves located just ahead of sample flowmeters that lead into each instrument. The oxygen analyzer, however, is downstream of the CO_2 analyzer, and it is zero-adjusted with either oxygen-free CO_2 calibration gas or N_2 gas and span-calibrated with air.

Thermal Efficiency Data Loggers

The commercial thermal efficiency rating method generally used in the industry today is the steady-state operation, flue gas heat loss method. This method uses only the measurement of flue gas CO_2 concentration and net temperature to determine air/fuel ratio (i.e., relative heat input), and unused heat energy ejected out the flue, from which the ratio of a pseudo heat-out (heat-in less flue gas heat loss) to heat-in is derived. This method is a useful indicator but does not account for many of the losses associated with furnaces in actual cyclical operation.

The combination of the cyclical nature of operation of fired-furnace heating systems and variables contributed by the control tolerances of the subsystems produces complex heat delivery profiles. It was concluded, however, that evaluation of the actual operating thermal efficiency would provide valuable new data and provide a more comprehensive evaluation of pollutant emissions, in terms of total pollutant emitted.

Because of the large number of variables affecting the operating cycle (e.g., weather, thermostat setbacks, control inconsistencies, etc.), a large number of cycles would have to be measured to provide a statistically valid

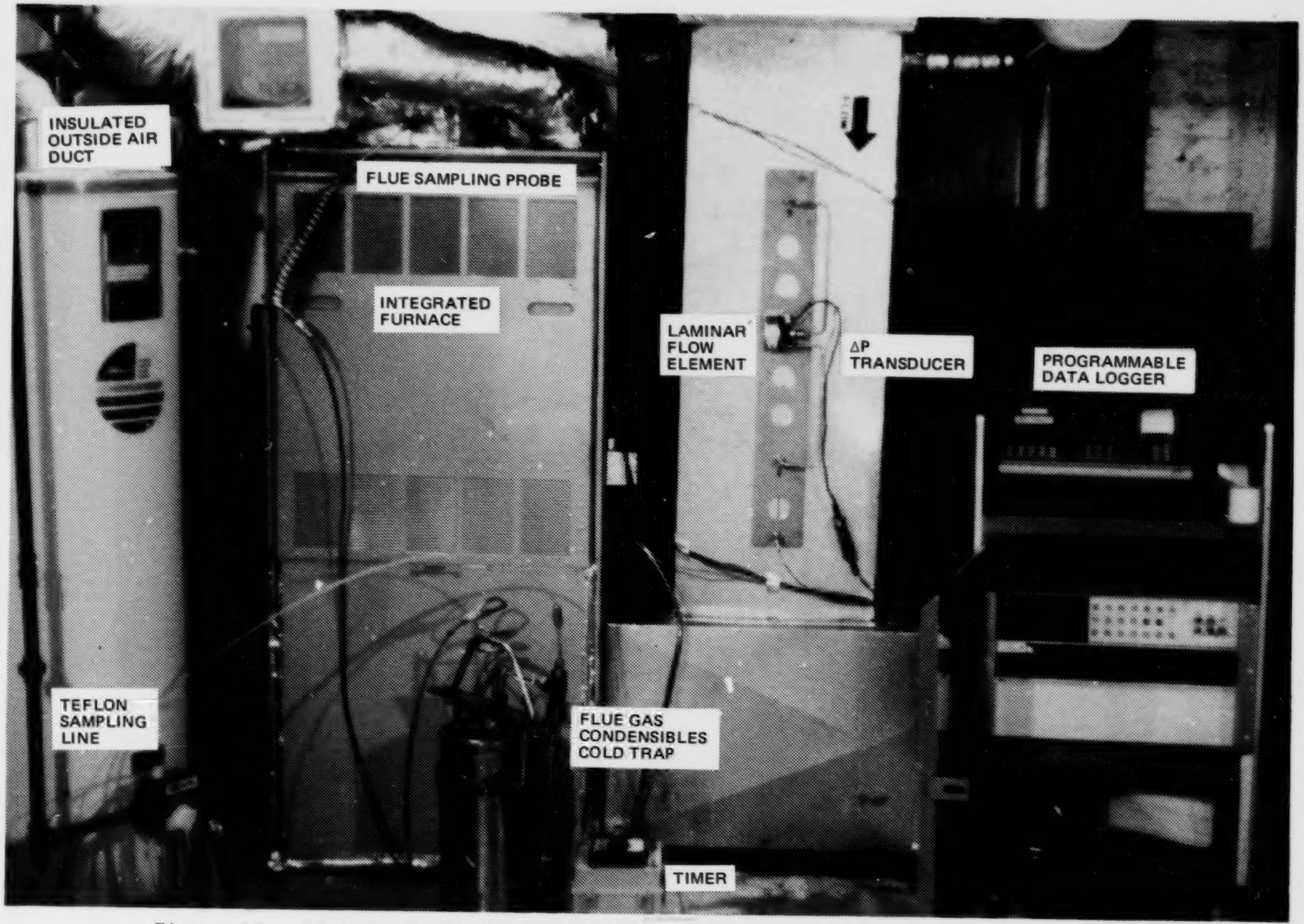

INSULATED OUTSIDE AIR DUCT
FLUE SAMPLING PROBE
INTEGRATED FURNACE
LAMINAR FLOW ELEMENT
ΔP TRANSDUCER
PROGRAMMABLE DATA LOGGER
TEFLON SAMPLING LINE
FLUE GAS CONDENSIBLES COLD TRAP
TIMER

Figure 11. Photograph of the Pond Site Installation of the Integrated Furnace with Efficiency Data Logger and Flue Gas Sampling System Attached

data base. To accomplish this task of evaluating installed operating efficiency, a programmable data logger system was assembled to continuously record firing cycle efficiency and timing parameters. Supplementing this system were time recording data loggers attached to the five other furnaces to accurately monitor furnace utilization. The ultimate objective of this dual path scheme was to establish overall heating season thermal efficiency values for all six furnaces by correlating efficiency to cycle timing through the programmable data logger information and applying the correlation to cycle timing data acquired over the entire season.

Programmable Data Logger – The cycle-averaged thermal efficiency measurement method devised for this field test effort is a derivative of the ANSI Z91.1-1972, "Performance Requirements for Oil-Powered Central Furnaces," (Reference 7) method, modified in some areas to improve measurement accuracies and extended to evaluate cyclical furnace operations. The ANSI Z91.1-1972 standards are steady-steady efficiency rating methods by the measurement of either warm-air heat output and oil throughput (Z91.1, Section 6), or flue gas heat loss (Z91.1, Appendix C). The measurement of warm-air heat output is the procedure selected for use in this program. The cycle-averaged thermal efficiency is determined by direct measurement of heat delivered to the dwelling during the operating cycle normalized by the amount of heat input into the furnace determined by timing the burner operation. The heat output is simply the cumulative measurement of warm air weight flow rate and temperature rise during each cycle. The heat input for each cycle is derived by timing the burner during each firing, and in the subsequent data reduction procedure, a period-average oil flow rate is applied that was established from the measurement of total fuel consumed divided by the total firing time recorded for the monitored period.

Two modifications to the ANSI method were instituted to improve accuracy: (1) A series electrical arrangement was chosen for the nine-thermocouple output temperature grid instead of the specified parallel arrangement, and (2) a calibrated air-flow measurement element was added for determining warm-air throughput.

The parallel thermocouple electrical arrangement specified by ANSI Z91.1 is prone to measurement errors under conditions of large thermal gradients in the flow field, and a failure of one thermocouple (open junction) in the grid is not easily detectable through analysis of the data. The chosen series electrical arrangement produces the simple sum of nine essentially independent (individual reference junctions) thermocouples. The resultant stronger output signal is influenced less by electrical noise and voltmeter inaccuracies, and a failure of any of the nine thermocouple junctions would immediately register as a zero reading, thus flagging the problem. All thermocouple circuits in the system are reference junctioned to provide accurate temperature measurements. All of the reference junctions are isolated in an insulated compartment to provide a relatively stable thermal reference, and the "floating" reference temperature is measured by a thermistor. The thermocouple outputs are measured, and the reference temperature correction is applied during the conversions to temperatures which are handled internally by the data logger controller.

The ANSI-specified method of measurement of weight flow rate of the warm-air flow is based on an assumption of uniform flow velocity profile in a large duct, which is unlikely to be true, especially in actual furnace installations. Therefore, a low pressure drop, laminar flow element system was assembled that permits the measurement of relatively high flow rates (∿1000 scfm) at very low pressure drops (∿0.1 in. of water).

The adaptation of the steady-state-firing ANSI specifications to a cycle-averaged method is solely a change in procedure. The programmable feature of the selected data logger system (Hewlett/Packard System 3051A) allows a logic scheme to be instituted into the controller of the monitoring system to accomplish the required procedure.

Figure 12 is a close-up of the central unit (H/P 3051A) showing the computer/controller (top), the digital multimeter (middle), and the 10-channel scanner (bottom) modules, while the data logger system can be seen in place in the photograph of the Pond installation (Figure 11). In Figure 11, the insulated thermocouple reference junction module can be seen (white module) in the bottom compartment of the data logger cabinet, and next to the data logger is the 0.457-m by 0.457-m (18-in. by 18-in.) laminar flow measuring element installed in the dwelling return air system. Figure 13 presents a schematic of the apparatus, while Figure 14 is a system control logic schematic. The system monitors two channels of ac voltage (sensing), five channels of temperature measurement (Chromel-Alumel thermocouples and a thermistor), and one channel of differential pressure information. Channel 1 senses burner power to determine the boundary of the firing cycle and the duration of heat input. Channel 2 senses warm-air fan power, which is only used as a signal for measurement of heat output parameters. Channel 3 is return air temperature required for both air flow rate and temperature gain calculations. Channel 4 is a series matrix of nine thermocouples to measure output air temperature. Channel 5 monitors maximum flue-gas temperature during the burner firing and is used in conjunction with Channel 8, burner inlet air temperature for calculation of a net flue-gas temperature. The temperature in the reference junction enclosure is monitored by Channel 7, a thermistor device, and the appropriate temperature correction is applied to all the thermocouple readings. Channel 6 is connected to a very low differential pressure tranducer, 0 to 138 Pa (0 to 0.5 in. WG), which measures the pressure differential across a laminar flow element in the return air ducting. This, in conjunction with the return air temperature (Channel 3), enables the weight flow rate of heated air to be calculated.

The logic schematic in Figure 14 does not represent the actual sequence of channels scanned; instead, the measured parameters are positioned closer to the factors in the decision process for clarity. A listing of the actual control code is presented in Appendix A. All channels are measured during each scan, but the data are retained only during the appropriate sequences in the firing cycle, thereby eliminating errors induced by reading of residual values. The

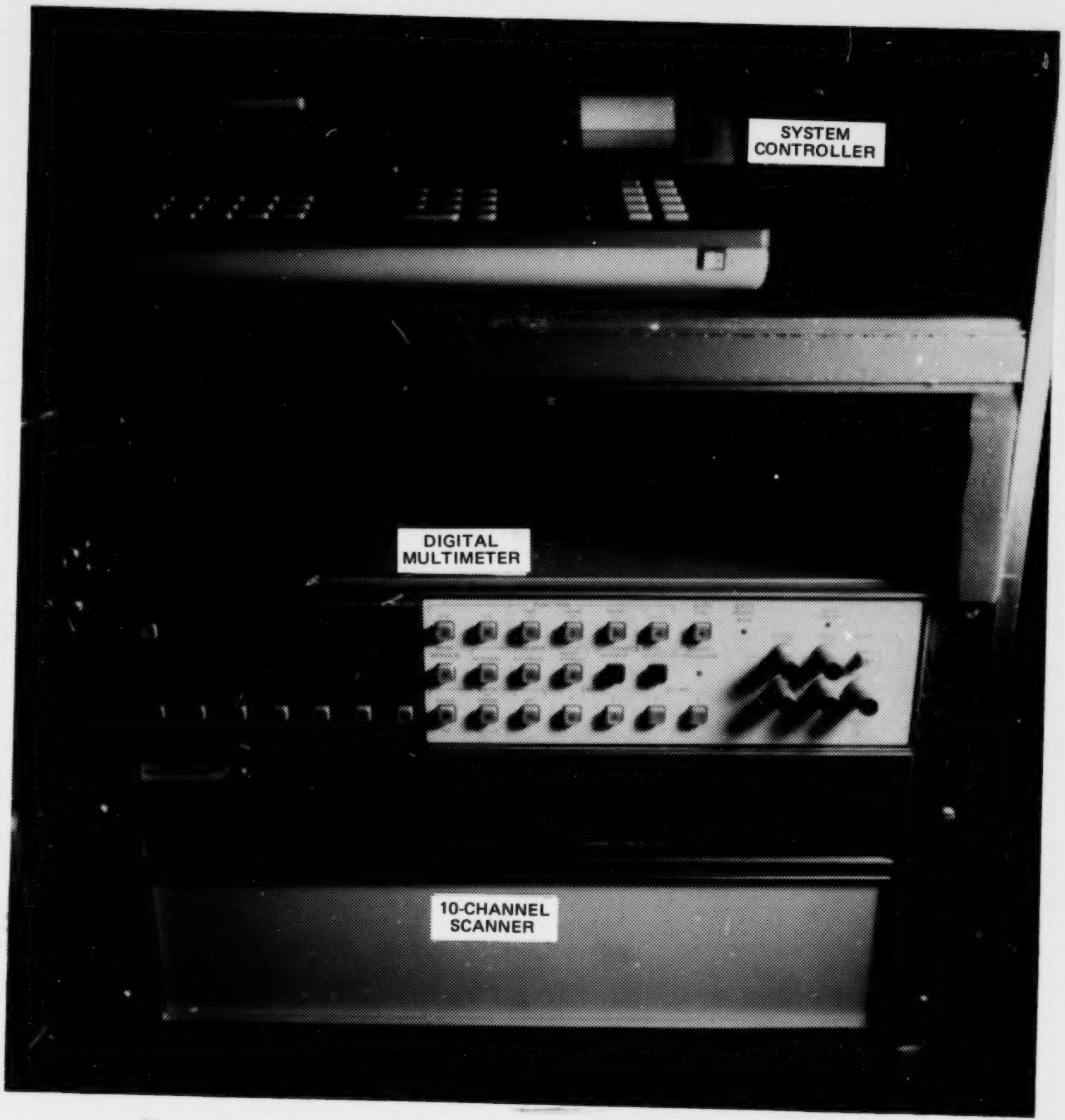

SYSTEM CONTROLLER
DIGITAL MULTIMETER
10-CHANNEL SCANNER

Figure 12. Photograph of the H/P System 3051A Programmable Data Logger Used to Monitor Thermal Efficiency of Installed Furnaces

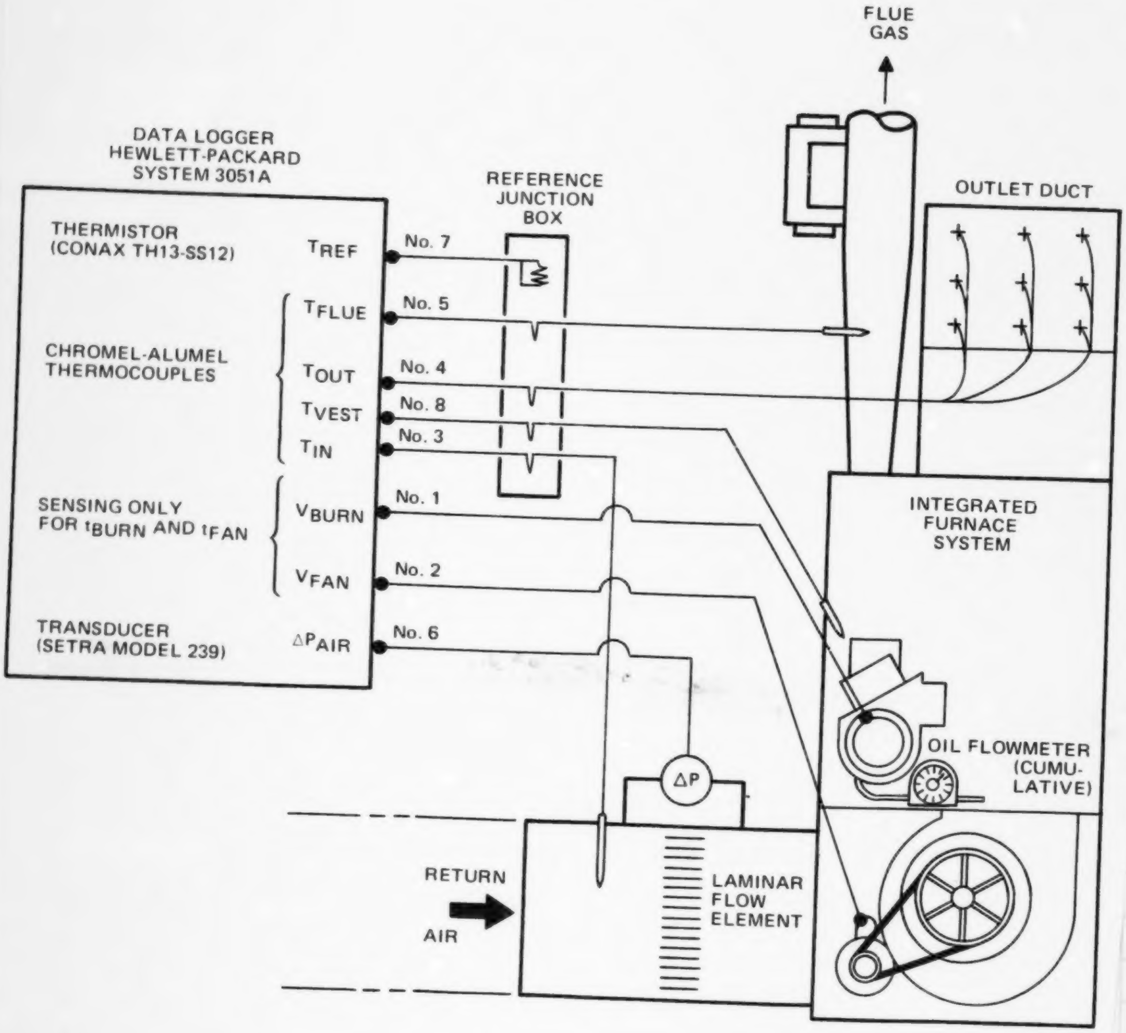

FLUE GAS
DATA LOGGER HEWLETT-PACKARD SYSTEM 3051A
REFERENCE JUNCTION BOX
OUTLET DUCT
THERMISTOR (CONAX TH13-SS12)
T REF
No. 7
T FLUE
No. 5
CHROMEL-ALUMEL THERMOCOUPLES
T OUT
No. 4
T VEST
No. 8
T IN
No. 3
SENSING ONLY FOR t BURN AND t FAN
V BURN
No. 1
V FAN
No. 2
TRANSDUCER (SETRA MODEL 239)
ΔP AIR
No. 6
INTEGRATED FURNACE SYSTEM
OIL FLOWMETER (CUMULATIVE)
ΔP
RETURN AIR
LAMINAR FLOW ELEMENT
8486-5

Figure 13. Schematic of Automatic Field Test Furnace Efficiency Data Acquisition System

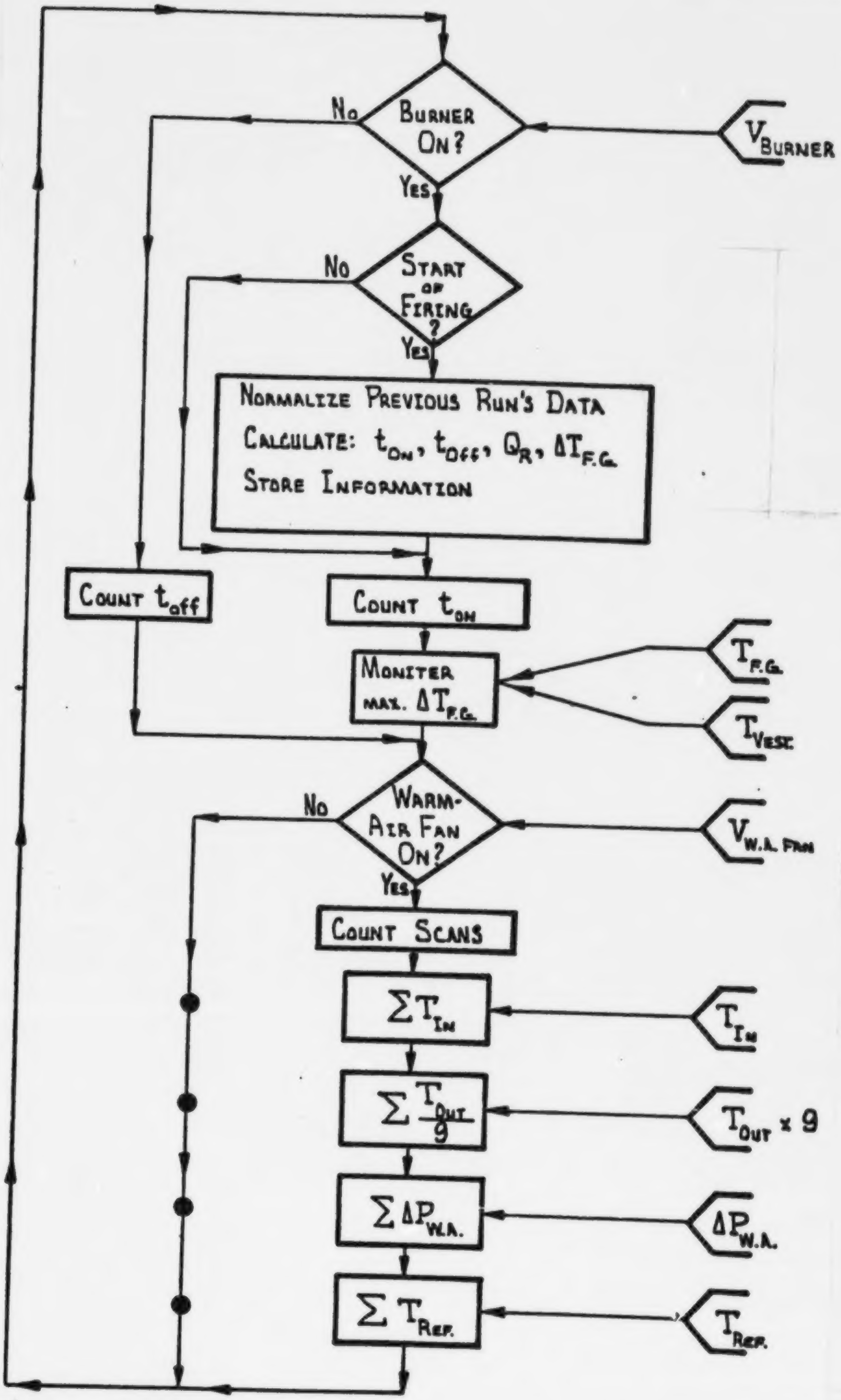

No
Burner On?
Yes
V BURNER
No
Start of Firing?
Yes
Normalize Previous Run's Data
Calculate: t ON, t OFF, Q R, ΔT F.G.
Store Information
Count t off
Count t ON
Moniter max. ΔT F.G.
T F.G.
T Vest.
No
Warm-Air Fan On?
Yes
V W.A. Fan
Count Scans
ΣT IN
T IN
Σ T OUT / 9
T OUT × 9
ΣΔP W.A.
ΔP W.A.
Σ T REF.
T REF.

Figure 14. Program Logic Schematic for the Cycle-Averaged Thermal Efficiency Data Logger Controller

overall logic is simple: A firing cycle is marked from the time the burner starts to the next burner start, discriminating between burner-on (i.e., heat in = $h_c \cdot W_{oil} \cdot t_{on}$) and burner-off times, and all heat delivered to the distribution system during this period is credited to this firing. This assumes that each firing is "blown down" to the prescribed level of residual heat set by the fan thermostatic control. Occasionally, abnormally terminated firings (over-temperature cutoff, thermostat setting change, etc.) violate the basic firing cycle assumptions and result in unusual efficiency values for some firings. The method of data reduction used (t_{on}-weighted efficiency averaging), however, alleviates these individual cycle anomalies by essentially summarizing total heat-out and total heat-in from all the firing cycles for the entire monitored period.

Upon first sensing voltage to the burner (start of firing), the controller: (1) processes the previous run's data; (2) stores t_{on}, t_{off}, max. $T_{fg\ net}$, and Q_{out} information; and (3) clears the registers for new information. Then the t_{on} count is started for the new firing, and instructions to monitor $T_{fg\ net}$ are set. The t_{on} count is maintained thereafter until burner voltage drops to zero (burner off), at which time the t_{off} count is initiated. The Q_{out} parameters (T_{in}, ΔP_{in} and T_{out}) are measured on every scan but are not retained until warm-air fan voltage is sensed, at which time the controller will retain these measured values in the form of summations of each parameter and account for the number of readings in the summation. This cumulative process is continued whenever fan-on is sensed, at any time, for any number of times during the cycle, thereby recording all heat delivered from the firing. At the end of the firing (marked by the start of the next firing), the summations are normalized by the number of readings, resulting in very precise average values derived from hundreds of readings during the firing cycle. These values are then used for the determination of total heat delivered by applying the total fan-on time, which is derived from the scan count, to the average warm-air flow rate and mean warm-air temperature rise:

$$Q_{out} = \bar{\dot{W}}_{wa} \cdot t_{fan} \cdot c_{p_{air}} \cdot (\bar{T}_{out} - \bar{T}_{in})$$

where

$$\bar{\dot{W}}_{wa} = \frac{\rho_{air} \cdot \bar{T}_{in}}{T_{std}} \cdot f\left(\frac{\Delta P}{N}\right) = \frac{\rho_{air} \cdot \bar{T}_{in}}{T_{std}} \quad \bar{\dot{V}}_{wa}$$

In cyclical operation, the furnace is technically not at steady-state conditions; therefore, the ANSI steady-state flue gas loss method of measuring furnace efficiency is not directly applicable. In laboratory tests, however, the furnace efficiency determined by the highest net flue gas temperature reading (typically, with a massive firebox, the last reading in a firing cycle) was indicative of the level of furnace performance. Therefore, the highest net flue gas temperature recorded during each firing is also stored along with the measured heat output data. This provides a qualitative cross-check should very unusual cycle-averaged efficiency data appear.

When data from 20 firings have accumulated in the temporary storage area of the data logger controller, they are transferred to permanent storage on magnetic tape. If, however, an on-time greater than 2.8 hours or an off-time greater than 27.8 hours has been recorded, the data transfer instruction is executed immediately to secure a significant time value in permanent storage. Data from a maximum of 4,300 firings can be stored on one magnetic tape cartridge. The controller also has an automatic start capability that enables it to reload the control program and restart the system should a power outage occur.

The rate of heat input (fuel oil flow rate) is determined over a long period of time, preferably the total duration of the monitored period, and so the cycle-averaged efficiencies are not determined at the time of acquisition. The measured fuel oil flow rate is determined at the end of the monitored period by noting the total fuel oil consumed and dividing by the total burner-on time accounted by the data logger system, then applying this value to the subsequent data reduction procedure. In the data reduction procedure, all the firings may be evaluated to derive an overall average efficiency value for the monitored period, and the efficiency averaging method found to be most meaningful is burner-on time-weighted averaging:

$$\eta_t = \frac{\Sigma(t_{on_i} \cdot \eta_{cyc_i})}{\Sigma t_{on}} = \frac{100 \cdot \Sigma Q_{out}}{\bar{\dot{W}}_{oil} \cdot h_c \cdot \Sigma t_{on}} = 100 \cdot \frac{\Sigma Q_{out}}{\Sigma Q_{in}}$$

where

$$\eta_{cyc_i} = \frac{100 \cdot Q_{out_i}}{\bar{\dot{W}}_{oil} \cdot h_c \cdot t_{on_i}}$$

and $h_c = 4.0137 \times 10^{10}$ J/m^3 (144,000 Btu/gal), Heat of Combustion.

Cycle timing parameters (t_{on} and t_{off}) are stored not only for determining the heat-input in each firing cycle to determine efficiency, but possibly to derive a correlation of cycle-averaged thermal efficiency to on and off periods of the cycles. It is anticipated that furnace thermal losses are consistent enough that they can be represented by the cycle timing parameters. For example, burner-on time may represent the magnitude of steady-state losses (cabinet losses and component heat-up), while burner-off time describes the standby losses. A simplified heat balance analysis of cyclical thermal efficiency may be:

$$\eta_{cyc} = \frac{Q_{out}}{Q_{in}} = \frac{Q_{in} - Q_{loss}}{Q_{in}} = 1 - \frac{Q_{loss}}{Q_{in}} = 1 - \frac{Q_{ss} + Q_{sb}}{Q_{in}}$$

where

$Q_{in} = h_c \cdot \dot{W}_{oil} \cdot t_{on} = C_o \cdot t_{on}$ (heat in)

$Q_{ss} = C_1 \cdot t_{on}$ (steady-state losses)

$Q_{sb} = C_2 \cdot t_{off}$ (standby losses)

which reduces η_{cyc} to:

$$\eta_{cyc} = 1 - \frac{C_1 \cdot t_{on} + C_2 \cdot t_{off}}{C_o \cdot t_{on}} = f \quad \frac{t_{on} + t_{off}}{t_{on}}$$

It appears likely that cyclical efficiency can be correlated to the cycle timing parameters; then, with cycle timing information, the performance of the furnace can be extrapolated over a wider span of operation, namely the entire heating season. This method of extrapolation was selected as the most economical procedure for estimating season-averaged furnace efficiency performance. One programmable data logger and five cycle time recording data loggers were rotated to all six installations during the season to establish the thermal efficiency characteristics of each furnace.

Cycle Time Data Loggers – To supplement the data acquired by the above system, furnace utilization data were recorded on the remaining five furnaces. To do this, specifications were drawn up for a recording clock system that would: (1) have digital output with 1-second time resolution; (2) monitor a 120 V ac circuit, recording the moments of voltage-on and voltage-off and distinguishing between the two; (3) provide 48-hour standby power to maintain correct time through power outages; (4) record a minimum of 8000 data points, preferably on magnetic cassette tapes; and (5) be compatible with a tape reader/computer input device. The system procured is an Instrumentation Technology Corp. Model 9676 (shown in Figure 15), a derivative of an earlier model, modified to the above specifications. The unit exceeds the specification in duration of standby power (>7 days) and recording capacity (~50,000 data points).

The device connects to a standard 120 V ac power receptacle which transforms and rectifies the power down to 12 V dc which charges a "gel" cell storage battery and powers the circuitry. The 12 V dc line power and the storage battery output are connected in parallel, thus providing two sources of power to the circuitry. A thumbwheel digital switch array on the front panel (see Figure 10) permits the initial setting of days (0 to 99), hours (0 to 24),

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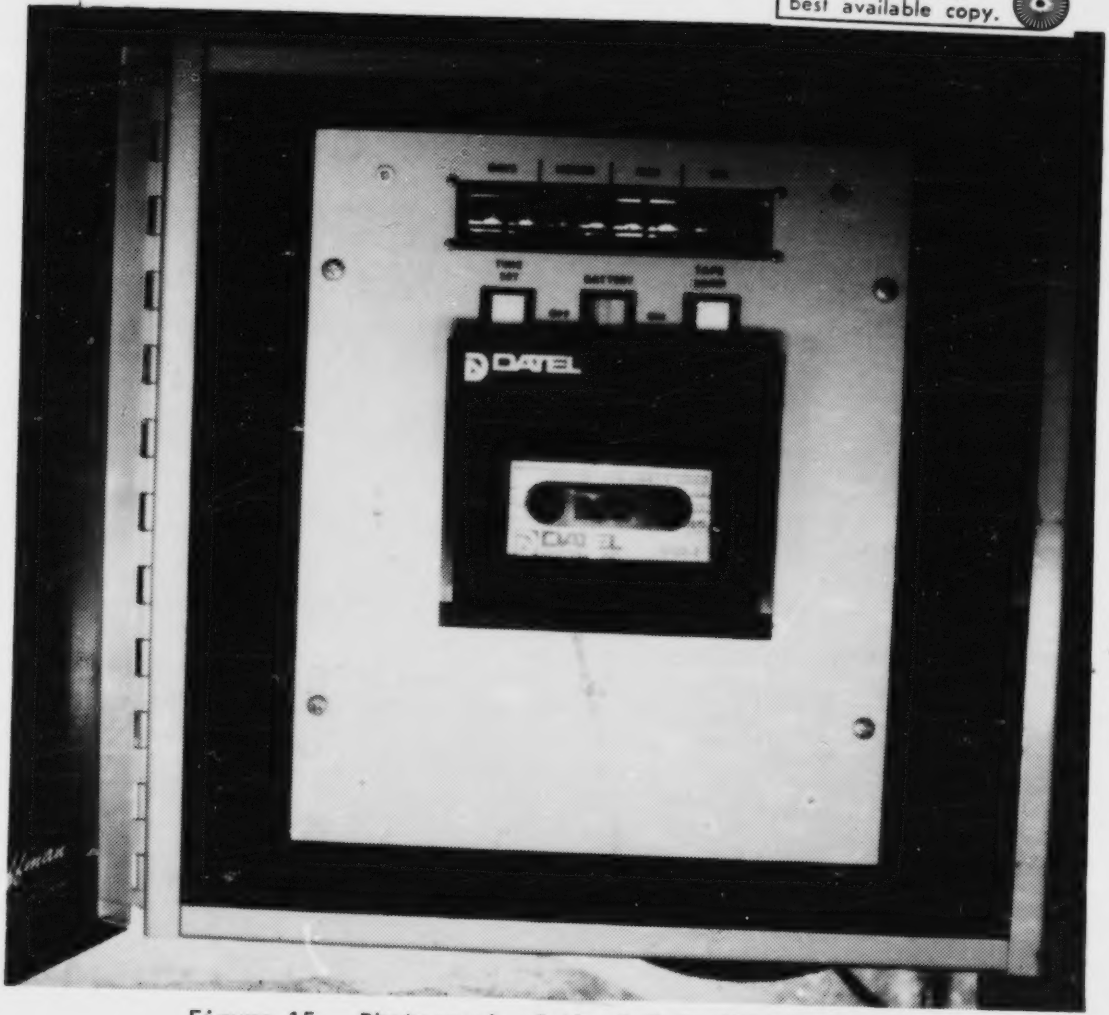

Figure 15. Photograph of the I.T.C. 9676 Furnace Cycle Timing Data Logger

minutes, and seconds. Thereafter, the progression of time is accounted for internally with no visual change in panel display. The sensing circuit connects directly from a case-mounted instrumentation receptacle to the burner power leads and responds to significant changes in sensed voltage level (e.g., 0 to 120 V ac - burner-on, 120 to 0 - burner-off). Three four-digit values are recorded at each voltage shift sensed: (1) days/hours, (2) minutes/seconds, and (3) on/off. The last parameter is an alternating alphanumeric character that labels whether the time recorded was a burner-on or a burner-off event to assure proper cataloging of the data. The data is recorded onto standard Phillips-type cassettes ("computer-certified" quality magnetic tape) utilizing a "Non-Return to Zero Incremental" (NRZI) digital recording format. The cassettes are retrieved and read into a GE440 timesharing computer via a Datel LPR-16 reader and a teletype terminal. Thereafter, the data are handled by standard Fortran language programs listed in Appendix A.

SECTION 5

FIELD TEST RESULTS

TEST OBJECTIVES

The scientific objectives of the field test were to maintain close-to-laboratory levels of pollutant reduction and demonstrate an ability to achieve improvement in fuel consumption by careful application of the low-emissions design criteria. Consistency of performance and maintainability of the furnaces were also of interest.

The goals set on the pollutant emission concentrations were derived from consideration of both laboratory results (References 4 and 5) and a field survey (Reference 6). The emission concentration limits are expressed on a cycle-averaged basis for a fixed operating cycle of 4 minutes on, 8 minutes off. The NO emissions goal was set at 0.65 g/kg of fuel burned, a reduction of approximately 65% below the average established by the field survey. The limits for CO and UHC emissions were set at 1.00 and 0.10 g/kg, respectively, allowing no compromise of these pollutants for achieving low NO. Smoke emissions at or below No. 1 smoke spot reading on the Bacharach smoke scale were deemed acceptable.

An improvement in gross thermal efficiency 10 percentage points above the average of the furnaces encountered in the field was another goal set for the integrated furnace system. Therefore, a low stoichiometric ratio (S.R.) operating condition, S.R. = 1.20, was also imposed to aid in achieving an improvement in fuel utilization.

The field test was originally planned to be conducted through one heating season (1977-78); however, minor malfunctions in the on-site automatic data recording devices resulted in interruptions in the data. Since the available data showed encouraging results and the furnaces showed no significant signs of degradation, the field test was extended to include a second heating season (1978-79) for the purpose of acquiring more data.

CLIMATIC CONDITIONS

Weather records from the Albany County airport and the Blue Hills Observatory (Milton, Massachusetts) show totals of 7055 degree-day and 6725 degree-day, respectively, for the field test period. The 1977-79 test period was the second and third of three unusually cold winter seasons in the Northeastern and Midwestern United States, with degree totals in Boston of 6755 and 6500, and in Albany of 7198 and 7095 for 1977-78 heating seasons, respectively. The test area encountered two severe winter storms in the months of January and February 1978. The second storm paralyzed the Boston area for 7 days, with more snowfall recorded in that area in a 24-hour period than that of the entire winter of 1972-73. Temperature extremes in the Boston area are buffered somewhat by the ocean mass (maritime climate effect), however, resulting in winter seasons warmer than those experienced in the Albany area (continental climate).

The above-reported degree-day values are based on the generally accepted 18°C baseline, from which any daily mean temperature (a simple average of the maximum and minimum temperatures) below this value is subtracted and presented as degree-days. The heating service subcontractor in the Albany area, however, has found that use of a 21°C baseline value applied to the mean temperatures measured at the Albany County airport results in a better representation of heating oil consumption of their clientele. This is primarily because of the relatively low location of the Albany County airport in the Hudson River Valley (i.e., warmer temperatures) compared with the location of the bulk of their customers. We have found this generally to hold true for the three Albany test locations and have adhered to the use of this method for the Albany data. All degree-day values reported hereafter in this paper for the Albany sites are based on the 21°C reference.

PERIODIC MONITORING

The field test monitoring schedule was set up on a monthly basis during the first test period and extended to nominally 6 weeks during the second period. The initial furnace checkout visit occurred early in October 1977, with eight subsequent monthly visits ending in June 1978 and six visits during the September 1978 through June 1979 period.

This relatively frequent schedule of field visits during the first heating seasons was influenced by consideration of many aspects. It was felt that an initial setup visit plus a minimum of four visits were required to establish a record of emissions performance. Added to this are requirements for: (1) moving the programmable data logger around to all six furnaces; (2) unknowns in servicing requirements of the "prototype" furnace design; and (3) unknowns in the weather. Therefore, a monthly schedule seemed most practical, allowing enough flexibility to provide for both the basic requirements and the unknown factors.

The field test cycle-averaged emissions measurements were obtained from fixed 4 minutes on/8 minutes off firing cycles which would be directly comparable to the baseline data obtained in the laboratory in the Phase I effort. In preparation for obtaining the field measurements, the dwelling thermostat control leads are disconnected and leads from a repeat cycle timer are connected. The furnace is then fired through several 4-on/8-off cycles to establish nominal temperature conditions for the emissions measurement cycles. The flue gas sampling is continuous through the firing cycle and the average readings are recorded. The CO and UHC readings change rapidly at burner start so the meter readouts are recorded on chart recorders for aiding in evaluating the cycle averages. Four smoke readings are taken during the 4-minute burner on period, the first at approximately 10 to 15 seconds after start (to allow the gases to reach the sampling point), and the remaining three at equally spaced intervals thereafter. The maximum net flue gas temperature is also noted for general reference.

Integrated Furnace Service

The integrated furnace test units performed relatively trouble-free considering their "prototype" status. Minor problems were encountered early in the first heating season, but these resolved to only two design/assembly-related problems. The first problem was safety circuit "lockouts" caused by the larger-than-normal static disc obscuring the illumination of the flame from the detector cell, and the second was caused by the spark electrodes being positioned too close to the oil nozzle, resulting in carbonization. These problems were resolved by installing a supplementary resistor in parallel with the flame detector cell to lower the overall electrical resistance and repositioning of the spark electrodes to a position approximately 0.00476 m (3/16 in.) further away from the oil nozzle.

On the first monitoring visit of the second heating season, all six test installations received "typical annual maintenance" servicing. This basically involved a thorough general inspection and replacement of the oil nozzle and line filters with new elements. The furnaces were then fired and stoichiometric ratio adjusted to the design conditions.

No failure of any major component occurred during the entire 1977-79 field test period. Post-test inspections of the furnaces revealed no anomalies nor signs of significant deterioration.

1977-78 Heating Season Pollutant Emissions Results

The general emissions characteristics from the furnaces in the two test areas differed notably during the first heating season. The three furnaces installed in the Albany area were generally more consistent than the Boston-area furnaces. It appears to be related to the fuel oil supplied to the sites, as the Albany-area sites were all supplied by one major name-brand oil supplier, while the Boston-area sites were supplied by two independent oil delivery companies.

Boston Area Installations

The results of the monthly pollutant emissions monitoring visits are presented in Table 4 for the Boston area. The data tables list the pollutant emission goals and monthly measurements. The monthly measurement values represent several firings during each visit that is listed in detail in Appendix B.

TABLE 4

1977-1978 INTEGRATED FURNACE FIELD TEST CYCLE-AVERAGED POLLUTANT EMISSIONS SUMMARY FOR THE BOSTON-AREA INSTALLATIONS

Field Test Location	Stoic. Ratio	CO g/kg	NO g/kg	UHC g/kg	Smoke Bacharach	T_{FG} Net ^{o}C	Date
Test Goals	1.20	≤1.00	≤.65	≤.100	0	--	
Woodbine St. Newton, MA Unit 5	1.23	0.65	.558	.065	0.5	134	Oct 1977
	1.23	0.39	.679	.028	0.7	132	Nov 1977
	1.21	0.80	.498	.027	0.8	135	Dec 1977
	1.22*	0.40	.589	.060	2.5	167	Jan 1978
	1.27	0.59	.579	.072	4.5	173	Feb 1978
	1.31	0.88	.845	.090	0.2	178	Mar 1978
	1.36	0.87	.876	.103	0.4	192	Apr 1978
	1.32	0.86	.952	.070	0	174	May 1978
	1.31	0.84	.619	.065	0	163	June 1978
Richard Road Needham, MA Unit 4	1.23	0.45	.690	.065	0.3	144	Oct 1977
	1.22	5.60	.350	.050	0.6	--	Nov 1977
	1.26	2.97	.447	.048	0.4	--	Dec 1977
	1.27*	0.68	.507	.019	0.5	140	Jan 1978
	1.45	0.54	.517	.033	0	147	Feb 1978
	1.24	0.68	.470	.036	0	156	Mar 1978
	1.19**	0.72	.585	.060	0	142	Apr 1978
	1.23	0.81	.610	.028	0	153	May 1978
	1.22	0.81	.647	.043	0	138	June 1978
Pond Avenue Brookline, MA Unit 1	1.22	0.32	.583	.065	0.5	158	Oct 1977
	1.30	0.78	.570	.069	2.0	174	Nov 1977
	1.21*	0.59	.532	.041	0	169	Dec 1977
	1.20*	0.55	.565	.020	0	169	Jan 1978
	1.24	0.47	.580	.038	0.5	169	Feb 1978
	1.31	0.46	.590	.043	0.1	186	Mar 1978
	1.18	0.60	.601	.038	0	170	Apr 1978
	1.23	0.59	.630	.019	0.1	164	May 1978
	1.19	0.60	.606	.018	0	140	June 1978

*New 0.75-70^{o}-A nozzle installed

**Flue pipe joints sealed

Most of the unanticipated variables in the field test were encountered at the three Boston-area installations, but these were not associated with the maritime climate effect. The field test furnaces encountered: (1) carbonization of the nozzle, (2) flue-pipe air leaks, (3) safety circuit lockouts, (4) dirty fuel supply system, and (5) unusually high fuel-bound nitrogen. The first item, nozzle carbonization, was related to the assembly of the integrated furnaces, which required a minor readjustment but has no effect upon the basic low- emission design criteria. The flue pipe air leaks affected the emissions performance because the determination of stoichiometric ratio conditions were based on flue gas analyses and this resulted in the burner being adjusted below design condition. There is no effect of these leaks upon the calculation of emission concentrations since the selected units of concentration of grams per kilogram of fuel burned is independent of the amounts of air involved; however, the calculation of stoichiometric ratio will be erroneously higher than the actual burner condition.

The last three items encountered in the Boston area relate to the fuel delivered in the field. Although troublesome, these unanticipated factors constitute the major differences between laboratory testing and field testing and are useful indicators of potential problems in large-scale emissions reduction efforts. An additional peculiarity of the Boston-area fuel was noted in a comparison made on the initial visit, when fuel oil from the stock used in the laboratory testing (SUNOCO-Toledo 9/76) was fired in each furnace (see Appendix B, Runs 658 to 691). The switch to the reference fuel oil, without any mechanical readjustment to the air shutter or pump output pressure, resulted in a 5% increase in stoichiometric ratio (i.e., lower oil flow rate) in all three Boston units while no significant shifts were noted at the Albany sites. Differences in viscous properties were suspected, but subsequent analyses show a greater difference between the Albany and the laboratory stocks than with the Boston stock. No apparent consequences to the emissions performance were noted so this characteristic was accepted as a field variant; however, consideration of design and operation of field equipment should include, in addition to tolerance for sludge and contaminants, allowances for such differences in inherent properties of the fuel oil.

Woodbine Site – The integrated furnace at this site (Unit 5) encountered all five of the problems listed above, most of which are apparent in the tabulation of the Woodbine emissions data in Table 4. Safety circuit lockouts were encountered in the second month of operation (November 1977). The carbonization of the nozzle culminated in January, requiring replacement of the nozzle and readjusting the combustion air control on the burner. Although not recognized at that time, the flue-pipe air leakage may have already been significant, causing erroneous high excess air readings and resulting in incorrect adjustment of the burner to a condition below its design stoichiometric ratio operating point. This possibility is reinforced by the high smoke readings during that period. There were also complaints from the hosts of noisy operation, requiring readjustment of the burner in February to a supposedly "above design specification" air setting. Fuel samples taken during this period showed significant amounts of bottom contaminants, which were thought to be the primary cause of the high smoke emissions.

Further evaluation of the unusual characteristics, however, led to the suspicion of misadjustment of the burner caused by air leaking into the flue. An internal gas sampling technique was tried on the subsequent visit (March 1978), and it revealed a significant discrepancy between the reading taken at the flue pipe (S.R. = 1.31) and that taken above the firebox (S.R. = 1.24). Another internal sample was taken at a point 0.229 m (9 in.) higher, at the entrance to the heat exchanger, and this also showed a higher excess air condition (S.R. = 1.28). This led to the belief that the leak was internal, probably at the union of the cast iron combustor and the carbon steel heat exchanger. The suspected internal air leak did not create any dangerous possibilities of flue gas leaking back into the dwelling since the combustion system operates at a negative pressure, so a post-test (end of 1977-78 heating season) inspection was scheduled and the subsequent data corrected to show the stoichiometric ratio reading at the firebox. These corrected values are shown in Table 4.

Disassembly of the unit revealed that the leak was external, caused by warping of the flue pipe at a very inaccessible area, on the backside of the connection to the furnace. The season-averaged stoichiometric ratio for the Woodbine unit, however, even including the suspect January and February readings, is 1.23, very close to design specification.

The CO and UHC averages for the 1977-78 season also satisfied the respective goals. The smoke emissions field test criterion is almost fulfilled with the season average, biased by the two months of "mistuned" operation. The flue-gas temperature reflects the effect of the soot buildup with a rise in net temperature starting at the time of the initial mistuning.

The season-averaged NO emission level for the Woodbine site is very close to the test goal, biased slightly high by three unusually high readings taken in March, April, and May. This was attributed to a fuel-bound nitrogen level of 200 ppm (April 1978, see Appendix B), more than twice that of other oil samples analyzed. The fuel-bound nitrogen concentration of the laboratory oil was analyzed to be 85 ppm, which resulted in nominally 0.65 g NO/kg fuel. The conversion of fuel-bound nitrogen to oxides of nitrogen, at these very low concentrations, is very nearly 100%, and applying this conversion rate to the 115-ppm difference in oil concentrations would result in an increase of 0.24 g NO/kg fuel, which is very close agreement to the 0.23-g/kg difference measured in April 1978. The source of this high-nitrogen fuel oil stock could not be traced because, unlike the gasoline market where the fuel stock is controlled by the major oil company up to the customers' cars, the fuel oil is resold and stored by several interim organizations that stored the fuel being received in any available tank with a minimum of records on specific stock. Also, during the mid-winter months, oil shortages occur and oil is accepted from almost any source at all levels of the marketing process. Additionally, there are no refinery guidelines on trace levels of fuel-bound nitrogen and locating the source would only be academic. It is important to note, however, the significant effect this subtle change in fuel property has at these low levels of NO concentrations.

Richard Site – The Richard site's integrated furnace encountered safety circuit lockouts in the first month, which were corrected on the first periodic field check. This site also experienced air leaks in the flue-pipe system. By January, a trend of increasing stoichiometric ratio conditions was noted (see Table 4), which at that time was assumed to be caused by degradation of oil nozzle performance. The oil nozzle was changed; however, smooth operation could not be attained at design stoichiometric ratio conditions, and the unit was set at an apparently high S.R. = 1.27 (flue-gas sample) condition. The stoichiometric ratio varied on the two subsequent visits, and on the third visit (April 1978) the internal sampling technique was used, confirming the existence of air leaks biasing the stoichiometric ratio readings. It was found that the actual operating conditions in the firebox were at design specifications, in spite of the high excess air levels measured in the flue pipe. All flue-pipe joints between the furnace and the flue-gas sampling point were then sealed with high-temperature aluminum tape. The subsequent flue-pipe excess air level reading was much lower, verifying operation at very close to the design operating conditions. This stoichiometric ratio reading can be extrapolated back to January 1978 with reasonable confidence, since the burner remained "untouched" during this period. Unfortunately, the burner was readjusted at that time so the extrapolation is not applicable to the two most suspicious readings (November and December) where the high CO emissions are suspected to be the cause of incorrect stoichiometric ratio conditions. The operating conditions over the heating season average to S.R. = 1.26, but with the discovery of the flue leaks and the evaluation of conditions in the earlier months, the average is estimated to be on the order of S.R. = 1.20-1.22.

The CO emissions measured at the Richard site were acceptable, with the exception of two measurements in the early months of the heating season where mistuned operation is now suspected. The CO profiles on these high cycle-averaged readings started with a significant "spike," followed by a relatively high and erratic CO trace through the 4-minute firing cycle. In January, the oil nozzle was changed because of carbonization, calling for readjustment of the air setting, which at that time appeared to be above design conditions but was later shown to be very close to design specifications. The CO emissions were then under control and remained so through the remainder of the test period; however, the two previous readings were high enough to bias the season-averaged value above the 1.0 g CO/kg fuel CO emission goal.

The NO emissions field test goal was satisfied throughout the heating season, resulting in a season-averaged value of 0.536 g NO/kg fuel. The goals for both UHC and smoke emissions were also achieved, with consistent performance below the stated limits.

Contaminants in the fuel oil were encountered in a different form at this site with no direct effect upon emissions performance. A "two-line" oil supply system was used at this site because of the underground tank installation. During the first month, the bypass return line plugged so the system was reverted back to a single-line system. High resistance in the primary oil line was encountered throughout the test period.

Pond Site — The Pond installation encountered only one problem that affected emissions performance, the accumulation of carbon on the nozzle. The problem was first noted at this site with a trend of increasing stoichiometric ratio (i.e., decreasing oil flow rate) requiring a nozzle change after only two months of service. It was first believed that the nozzle may have been "off specification," but when another nozzle change was required on the following visit, a closer examination was made of the nozzle and burner assemblies. It was then determined that the electrodes were positioned too close to the nozzle, and repositioning was effected on this and all other test units. Thereafter, with the exception of one anomalously high reading in March, which may have been attributable to characteristics of the fuel oil delivered before that visit, the stoichiometric ratio remained near design conditions. The limits on CO, NO, and UHC emissions were never exceeded at any time during the field test. The smoke emissions exceeded the test limit only once during the period of degraded nozzle performance, but the average for the season is well within specifications. All pollutant emissions goals were achieved at the Pond installation.

Albany Area Installations

The three integrated furnace field test installations in the Albany, New York, area performed relatively trouble-free through the entire test period. Two "no-heat" calls were received by the heating service subcontractor, but these were not attributable to the integrated furnaces, and only one incidence of nozzle carbonization was encountered. The results of the monthly emissions monitoring visits are presented in Table 5.

Gravon Site — The Gravon site showed a slight rise in stoichiometric ratio (see Table 5), and in February, when No. 1 Bacharach smoke reading was measured, carbonization of the nozzle was suspected. Removal of the nozzle showed only minor surface blackening, however, and the smoke reading persisted with a new nozzle installed. The burner was adjusted to its as-found condition of S.R. = 1.28, in keeping with the "minimum tampering" field-test guideline. Subsequent checks with the firebox combustion gas sampling method confirmed that the higher stoichiometric ratio measurements obtained in the flue pipe were correct (see Appendix C) and not attributable to air leaks. The isolated smoke trace recorded in February was probably induced by a fuel delivery the previous day, agitating bottom contaminants into suspension in the oil. The cause of the drift in stoichiometric ratio was not identified, possibly fuel induced, but the condition recovered to near design point at the end of the heating season. All pollutant emissions remained stable and controlled throughout the heating season at this installation, achieving all the field test pollutant emissions goals.

Stovepipe and Fissette Sites — The Stovepipe installation did encounter a nozzle carbonization condition, which was corrected by nozzle replacement and readjustment of the spark electrodes. The Fissette site showed no indication of nozzle problems and completed the heating season with no readjustments. The integrated furnace test units at both of these installations showed a peculiar CO emissions characteristic, the cause of which has not yet been identified.

TABLE 5

1977-1978 INTEGRATED FURNACE FIELD TEST CYCLE-AVERAGED POLLUTANT EMISSIONS SUMMARY FOR THE ALBANY-AREA INSTALLATIONS

Field Test Location	Stoic. Ratio	CO g/kg	NO g/kg	UHC g/kg	Smoke Bacharach	T_{FG} Net °C	Date
Test Goals	1.20	≤1.00	≤.650	≤.100	0	--	
Gravon Road Delmar, NY Unit 2	1.22	0.41	.590	.028	0	159	Oct 1977
	1.22	0.52	.586	.082	0	160	Nov 1977
	1.24	0.49	.494	.042	0	153	Dec 1977
	1.31	0.52	.522	.050	0	160	Jan 1978
	1.28*	0.68	.527	.039	1.0	181	Feb 1978
	1.25	0.56	.529	.057	0	148	Mar 1978
	1.29	0.78	.585	.036	0	166	Apr 1978
	1.27	0.67	.641	.034	0	152	May 1978
	1.24	0.53	.676	.037	0	147	June 1978
Stovepipe Road Clarksville Unit 6	1.21	1.12	.466	.018	0	137	Oct 1977
	1.21	2.23	.310	.110	0	150	Nov 1977
	1.31	1.22	.420	.040	0.4	146	Dec 1977
	1.23*	0.49	.540	.019	0	168	Jan 1978
	1.20	0.52	.476	.027	0.1	176	Feb 1978
	1.23	0.65	.613	.046	0	161	Mar 1978
	1.21	0.72	.583	.024	0	158	Apr 1978
	1.21	0.75	.535	.018	0	--	May 1978
	1.18	1.25	.636	.018	0	161	June 1978
Fissette Drive Feura Bush, NY Unit 3	1.22	2.24	.552	.064	0	126	Oct 1977
	1.19	1.27	.525	.400	0	152	Nov 1977
	1.20	0.83	.493	.063	0	132	Dec 1977
	1.18	0.55	.521	.036	0	138	Jan 1978
	1.19	0.76	.582	.050	0	148	Feb 1978
	1.24	0.65	.493	.043	0	149	Mar 1978
	1.20	0.76	.529	.050	0	166	Apr 1978
	1.19	0.91	.485	.045	0.1	147	May 1978
	1.19	1.46	.637	.061	0	134	June 1978

*New 0.75-70°-A nozzle installed

During the warmer periods of early fall and late spring, the units show unusually high start spikes on the CO emissions profile, resulting in the cycle-averaged values being above specifications. Some effect on UHC emissions is also noted during this period. This CO emission characteristic improved during the colder midwinter period, and the CO emissions were well below the 1.0 g/kg field test goal. Since the emissions measurements are taken on a fixed-firing cycle, the temperature of the furnace components at start is relatively equal and not greatly influenced by changes in ambient temperature. The temperature of the oil transported into the furnace varies with basement temperature, however, and it is suspected that this may have an effect on the pump delivery characteristics at startup. The duration of the phenomenon is very short, making it difficult to isolate its cause. Because of the much improved performance during the colder months, the season-averaged CO emission levels for both installations are right at the limit of 1.0 g/kg. The NO, UHC, and smoke emissions for both sites are all well under the season-averaged emissions limits, thus achieving all the field-test emissions goals.

1978-79 Heating Season Pollutant Emission Results

The design of the integrated furnace prototypes had been demonstrated to be basically sound, and they operated reliably through the severe winter of the first test period. The pollutant emissions performance showed no significant degradation after a complete heating season, so the number of site visits was reduced to six for the second heating season, one for initial servicing and setup and five subsequent monitoring visits.

Fuel oil in the Northeastern States was again in short supply during the second test period and the quality of the oil delivered degraded through the winter. More "heavy bottom" contaminants appeared in the line filter canisters, many of the fuel samples taken were cloudy (i.e., colloidal contaminants), and higher fuel-bound nitrogen-containing oil appeared at five of the six sites.

Boston-Area Installations

The results of the pollutant emissions monitoring visits for the Boston-area installations during the second test season are presented in Table 6. Although the integrated furnace at the Woodbine site was disassembled for inspection, no cleaning or repair was conducted. None of the furnaces showed any significant signs of deterioration, and the second test period was accomplished with no interruption of heating service.

Woodbine Site – The Woodbine site started the second heating season slightly above the NO goal but with all of the carbonaceous pollutant emissions within field test goals. On the subsequent visit, however, the smoke emission reading had risen to No. 1 Bacharach scale and another increase in the NO concentrations was noted. The fuel oil sample was cloudy, indicating colloidal contaminants. The smoke emissions continued to increase to a high of No. 4 Bacharach scale reading at midwinter (with a new nozzle), then improving to No. 1.5 by the end of the season. The NO concentrations were high and erratic

TABLE 6

1978-1979 INTEGRATED FURNACE FIELD TEST CYCLE-AVERAGED POLLUTANT EMISSIONS SUMMARY FOR THE BOSTON-AREA INSTALLATIONS

Field Test Location	Stoic. Ratio	CO g/kg	NO g/kg	UHC g/kg	Smoke Bacharach	T_{FG} Net °C	Date
Test Goals	1.20	≤1.00	≤.65	≤.100	0.0	--	
Woodbine St. Newton, MA Unit 5	1.23	0.68	.765	.056	0.0	149	Sep 1978
	1.29	0.60	.835	.064	1.0	149	Oct 1978
	1.27	0.65	.673	.054	1.5	148	Dec 1978
	1.24*	0.72	1.041	.039	4.0	--	Jan 1979
	1.23	0.85	.908	.065	2.0	171	Mar 1979
	1.23	0.49	.895	.034	1.5	172	Jun 1979
Richard Road Needham, MA Unit 4	1.22	0.42	.661	.023	0.0	147	Sep 1978
	1.22	0.54	.705	.037	0.5	152	Oct 1978
	1.29	0.60	.682	.049	0.7	161	Dec 1978
	1.29	0.72	1.119	.059	0.5	178	Jan 1979
	1.21	0.48	.877	.055	1.0	164	Mar 1979
	1.21	0.59	.633	.046	1.0	159	Jun 1979
Pond Avenue Brookline, MA Unit 1	1.23	0.65	.715	.022	0.0	141	Sep 1978
	1.31	0.61	.819	.040	0.5	--	Oct 1978
	1.31	0.49	.694	.045	0.7	--	Dec 1978
	1.31	0.52	.795	.060	0.5	163	Jan 1979
	1.30	0.78	.872	.065	1.0	180	Mar 1979
	1.24	0.53	.816	.028	1.0	171	Jun 1979

*New 0.75-70°-A nozzle installed

throughout the season as an assortment of high fuel-bound-nitrogen fuel deliveries were being received, averaging 0.853 g/kg for the season. The CO and UHC emissions remained within test goals throughout the heating season.

Richard Site — This furnace installation also received a number of deliveries of high fuel-bound-nitrogen oil containing significant amounts of colloidal contaminants. The NO emissions followed a similar profile to that of the Woodbine site (same oil delivery company) through the heating season. The smoke emissions increased throughout the period but reached only No. 1 Bacharach at the end of the season, remaining within test goals. The CO and UHC remained well within the goals, while the stoichiometric ratio drifted somewhat but returned to specifications near the end of the season.

Pond Site — This site is supplied by a different independent oil dealer, but it also occasionally received high-nitrogen oil. The NO emissions fluctuated throughout the season, rising to a high of 0.872 g/kg. All carbonaceous pollutant emissions goals were achieved; the smoke emission increased during the season but remained within test specifications.

Albany-Area Installations

The test furnaces in the Albany area operated more consistently than the Boston-area units, with generally better oil (fewer contaminants) received by the sites. The results of the pollutant emissions monitoring visits are summarized in Table 7.

Gravon Site — They received a delivery of oil just prior to the start of testing, and an NO level slightly above test goals was noted on the initial visit. The same level was measured on the following visit, a month later, since very little heating was required during the month. By December, however, the site had received another delivery of oil and the NO concentrations showed a marked drop.

The January visit revealed a No. 4 Bacharach smoke attributed to a sludge-coated nozzle. The oil sample showed an extremely black-colored oil had been delivered to the site. Speculation was that No. 4 oil might have been inadvertently mixed in the handling; however, a check of the API gravity resulted in a reading of 38^{o}, well within No. 2 oil specifications ($\geq 33^{o}$ API). A replacement of the oil nozzle was beneficial, but subsequent visits showed a gradual increase to 1.1 Bacharach scale. The site also received a delivery of high-nitrogen-content oil in late February which resulted in a sudden increase in the NO remaining through the end of the heating season. This furnace was one of two tested in the laboratory following the field test and demonstrated NO emissions within test goals with the oil available in the laboratory. The CO and UHC emissions remained controlled throughout the heating season.

Stovepipe Site — The integrated furnace unit at this installation performed flawlessly throughout the second season. This furnace showed an unusual CO and UHC start spiking characteristic during the second season, with only a new oil nozzle replacement during the annual servicing. The CO and UHC emissions both

TABLE 7
1978-1979 INTEGRATED FURNACE FIELD TEST CYCLE-AVERAGED POLLUTANT EMISSIONS SUMMARY FOR THE ALBANY-AREA INSTALLATIONS

Field Test Location	Stoic. Ratio	CO g/kg	NO g/kg	UHC g/kg	Smoke Bacharach	T_{FG} Net $^{\circ}C$	Date
Test Goals	1.20	≤1.00	≤.650	≤.100	0.0	--	
Gravon Road Delmar, NY Unit 2	1.21	0.59	.752	.033	0.0	143	Sep 1978
	1.21	0.40	.753	.025	0.1	152	Oct 1978
	1.21	0.42	.687	.029	1.0	167	Dec 1978
	1.26*	0.35	.644	.032	0.6	146	Jan 1979
	1.29	0.52	.880	.079	1.0	167	Mar 1979
	1.32	0.84	.861	.050	1.1	178	Jun 1979
Stovepipe Road Clarksville Unit 6	1.21	0.69	.550	.032	0.0	152	Sep 1978
	1.21	0.56	.601	.019	0.6	165	Oct 1978
	1.21	0.48	.669	.032	0.5	168	Dec 1978
	1.20	0.48	.631	.045	0.6	163	Jan 1979
	1.21	0.48	.670	.032	0.5	165	Mar 1979
	1.23	0.63	.661	.032	0.7	166	Jun 1979
Fissette Drive Feura Bush, NY Unit 3	1.21	1.14	.631	.065	0.0	133	Sep 1978
	1.21	0.76	.568	.041	0.2	141	Oct 1978
	1.27	1.19	.685	.067	0.5	145	Dec 1978
	1.25	0.80	.638	.066	0.5	147	Jan 1979
	1.21	0.51	.694	.101	0.5	166	Mar 1979
	1.28	1.33	.726	.085	0.5	152	Jun 1979
	↓	1.31	↓	.097	New Pump		Jun 1979
		0.85		.068	Electrode Adj.		Jun 1979
		0.88		.068	New Clutch		Jun 1979

*New 0.75-70°-A nozzle installed

remained well within the field test goal specifications. Although the NO emissions lingered on both sides of the goal level, the season average is 0.63 g/kg, satisfying that requirement. The smoke emissions remained well under control throughout the test period.

Fissette Site — This installation continued to show the unusual CO start spikes during the periods of milder weather in the second test season. The UHC emissions, however, were improved and remained well under control at all times. The phenomenon was thought to be caused by unusual oil pump startup characteristics that delivered the full flow rate a fraction of a second later, or perhaps a slipping centrifugal clutch drive. (The oil pump was coupled to the motor via a centrifugal clutch for a "cleaner" starting and stopping of oil delivery.) Immediately following the basic monitoring measurements on the final visit, the pump from the Gravon unit, one that showed no such emissions characteristics, was installed and fired. The results, also presented in Table 7, showed no difference in the CO emissions. The spark electrode assembly was then removed and readjusted to a slightly wider spark gap, from ~0.0032 m (0.128 in.) to ~0.0048 m (185 in.), which results in a longer spark that is blown further out from the burner head. The readings showed markedly lower CO start spikes as seen in Table 7. A subsequent test with the replacement of the clutch drive showed no further improvement.

The NO emissions remained very close to the test goal level throughout the heating season, with a delivery of probably high fuel-bound-nitrogen oil being delivered between March and June 1979, influencing the last NO measurement. The smoke readings showed a trace at start, but the averages for the firing cycles were well below the test goals.

Field Test Emissions Performance

The field test pollutant emissions goals were based on overall heating season performance. The 1977-78 season-averaged (equally weighted readings) pollutant emissions concentrations for all six sites are presented in Table 8 along with the field test goals. These averages show that except for the results of occasional mistuning at the Woodbine site resulting in smoke and at the Richard site resulting in high CO emissions, all pollutant emissions goals were generally satisfied.

Although mistuned operations caused by air leaking into the flue systems at Woodbine and Richard sites were subsequently confirmed by internal sampling of combustion gases, several suspiciously high emissions readings could not be linked directly to these readings since some parameter (e.g., air setting, oil nozzle, etc.) had been changed in the interim period. Therefore, a statistical error evaluation analysis was conducted on both the Woodbine and the Richard sites' monthly emissions histories to determine if the suspicious readings could be shown to be caused by errors (in this case, misadjustment). The "Thompsons' Tau Technique" was applied (see Analysis 3, Appendix F) to identify "outliers," that is those points lying out beyond the "scatter" of the data set. This is a statistical error analysis method that establishes a limit of

TABLE 8

SUMMARY OF 1977-78 HEATING SEASON POLLUTANT EMISSIONS AVERAGES FROM THE INTEGRATED FURNACE SYSTEMS

Field Test Location	Stoich. Ratio	CO (g/kg)	NO (g/kg)	UHC (g/kg)	Smoke Bach-arach	Net T_{FG} (^{o}C)
Test Goals	1.20	≤1.00	≤0.65	≤0.100	≤1.0	-
Woodbine Street Newton, MA	1.23	0.70	0.688	0.064	1.1 (0.6)	161
Richard Road Needham, MA	1.26 (1.23)	1.47 (0.96)	0.536	0.042	0.2	146
Pond Avenue Brookline, MA	1.23	0.55	0.584	0.039	0.4	167
Gravon Road Delmar, NY	1.26	0.57	0.572	0.045	0.1	158
Stovepipe Road Clarksville, NY	1.22	0.99	0.509	0.036	0.1	157
Fissette Drive Feura Bush, NY	1.20	1.05	0.535	0.090	0	144
Test Claims	≤1.25	≤0.73	≤0.590	≤0.050	≤0.1	-

deviation from the sample mean based on the sample size ("tau" criteria established by Thompsons) and the standard deviation. Any specific data point lying further from the sample mean than the deviation limit is considered an "outlier," a point influenced by other factors (e.g., errors, malfunction, etc.) and not belonging to this data set. One of the high smoke readings at Woodbine (February 1978) and one of the high CO readings at Richard (November 1977) were rejected by this criteria, and the recalculated emission averages are shown in parentheses in Table 8. Using these values, the two parameters are now within the field test goals. The evaluation included the data from all the sites, and although a few other points were identified by the error analysis evaluation, they were attributable to known causes and were not reevaluated.

Statistical tests were also conducted on the minimum emission levels that can be claimed from the field test results. A "null hypothesis" evaluation was applied (see Analysis 4, Appendix F) to the emissions data in which assumed hypotheses are tested against the available data, and the false or "not-false" states are determined. The conditions "satisfying" (i.e., not rejecting) the null hypotheses are then statistically true "claims" which can be compared against the goals. The hypotheses were set up to test the monthly values of measured pollutant emission levels against chosen values of limits, to converge on minimum values of each pollutant species which would satisfy the hypotheses for all six test sites, thus establishing the minimum pollutant emissions "claims" for the field test. A 5% significance level was selected as the test criteria, meaning that there is only a 5% probability that the claims are not correct. The resultant values for each pollutant are listed at the bottom of Table 8, showing all pollutant emissions goals can be claimed to have been accomplished.

The season-averaged pollutant emissions results of the 1978-79 heating season are presented in Table 9. The values presented are the season averages of each site and of each emission parameter for all sites over the test period. Since there were no periods of mistuned operation or any unusual circumstances encountered during the test period, statistical analyses to determine the validity of each measurement were not required. Additionally, the influence of the high fuel-bound-nitrogen oil upon the NO emission readings imposes a bias that would make a minimum NO emission "claim," using a null hypothesis statistical evaluation, subject to qualification. So the overall season averages are simply stated in terms of simple arithmetic averages of results from all six monitoring visits.

The 1978-79 season-averaged values of all the carbonaceous pollutants are well under the field test goals. The stoichiometric ratio again drifted upward slightly, but with no significant detrimental effects. The variation in stoichiometric ratio may be due to varying properties of the fuel oil as was seen in the initial visit in October 1977 when a switch to the laboratory oil stock produced significant changes in stoichiometric ratio conditions without any mechanical changes in adjustment to the burner.

TABLE 9

SUMMARY OF THE 1978-79 INTEGRATED FURNACE FIELD TESTS POLLUTANT EMISSIONS AVERAGES

Field Test Site	Stoich. Ratio	CO (g/kg)	NO (g/kg)	UHC (g/kg)	Smoke	Net T_{FG} (^oC)
Test Goals	1.20	1.00	0.65	0.100	1.0	-
Boston Area						
Woodbine	1.25	0.67	0.860	0.051	1.7	158
Richard	1.23	0.54	0.794	0.045	0.6	160
Pond	1.28	0.68	0.776	0.044	0.6	164
Albany Area						
Gravon	1.25	0.51	0.764	0.042	0.6	159
Stovepipe	1.21	0.55	0.634	0.032	0.5	163
Fissette	1.24	1.12	0.659	0.071	0.4	147
Season Average	1.25	0.64	0.744	0.046	0.7	-
Standard Deviation	0.038	0.22	0.127	0.016	0.7	-

The NO emission average is slightly above test goals; however, the cause is known to be the above-normal fuel-bound-nitrogen concentrations in the fuel oil delivered to the sites. Two of the furnaces were tested in the laboratory following the field test, and the results showed acceptable NO emission levels with the reference fuel stock, 90-ppm fuel-nitrogen content (see Supplementary Laboratory Tests section). The season-averaged smoke emission rose slightly from the previous season's average.

This rise is partly caused by lower quality (heavy bottom and colloidal contaminants, extremely dark oil, etc.) of the fuel oil available during the 1978-79 heating season. This condition was widespread in the Northeast, as several of the trade magazines noted the greater number of problems being encountered in the oil heating industry from clogging, sludging, and even freezing (water contamination) of oil feed systems. Later laboratory tests showed that "buildup" on the inside surfaces of the furnace also influences the formation of smoke. The smoke emissions characteristic, then, is the only pollutant emission parameter that indicates some deterioration of performance with usage; however, it is difficult to estimate the rate of degradation since it is greatly influenced by the quality of the oil supplied.

Fuel quality is a significant factor in very long-term furnace emissions performance in the field. The field test started with the replacement of the oil tank at the Gravon site because of contaminants and corrosion in the 20-year-old system. Additionally, during the heating season bottom contaminants were noted at Woodbine and Richard sites which appeared to have affected the smoke emissions and inhibited fuel flow rate. Although all of the fuel supply systems have in-line filters in the oil supply line, the filtering element is a spool of loosely wound yarn-like cord designed to filter only large-size particulate contaminants and tolerate fair amounts of sludge contaminants without plugging. The latter characteristic is to provide oil to the furnace under adverse conditions, but it also is indicative of the quality of fuel oil that is often encountered in the fuel oil market. Although better filtering elements are readily available that can be adapted to this application, the primary difficulty is the lack of attention to the oil supply system by the homeowner, since the effect is usually of no apparent consequence. This would require more elaborate filter assemblies (i.e., more expensive) with multi-elements and bypass valves to cope with the wide variations in fuel quality and the lack of attention. In addition to the present problems, the quality of fuel oil is not likely to improve. Conversations with D. W. Locklin (co-author, Reference 6) revealed that some petroleum refining organizations are already considering producing a lesser grade of residential heating oil that would be heavier than No. 2 grade (i.e., more likely to sludge), but not to the former No. 3 grade specifications. A compilation of all oil analyses made during the test period is presented in Appendix B.

The field test effort demonstrated that significant reductions in NO_x emissions can be achieved using conventional furnace construction techniques. The experimental furnace components were fabricated using methods amenable to mass production, and the furnaces required no special maintenance considerations. Two consecutive winter seasons' duty resulted in no notable

TABLE 10
TABULATION OF INTEGRATED FURNACE SHORT-TERM AVERAGE THERMAL EFFICIENCY PERFORMANCE DURING THE 1977-78 HEATING SEASON

Furnace Test Site	Furnace Efficiency ($\bar{\eta}_t$,%)	Furnace Usage ($\bar{t}_R$,%)	Average Degree-Day/Day	Number of Firings Evaluated	Monitored Period
Woodbine Street MA (Unit 5)	80.6	36	24	3,354	Oct - Dec 1977
Richard Road MA (Unit 1)	77.1	32	37	2,044	Dec 1977 - Jan 1978
Pond Avenue MA (Unit 1)	73.0	34	43	518	Jan 1978
Gravon Road NY (Unit 2)	70.5	29	52*	574	Feb - Mar 1978
Stovepipe Road NY (Unit 6)	73.5	14	39*	990	Mar - Apr 1978
Fissette Drive NY (Unit 3)	71.8	9	17*	781	Apr - Jun 1978
Overall Average	74.4 (±3.75)				

*Degree-days based on 70°F reference

where $$\bar{\eta}_t = \frac{100 \cdot \Sigma t_{on} \cdot \eta)}{\Sigma t_{on}} = \frac{\frac{100}{\dot{w}_{oil} \cdot h_c} \Sigma Q_{out}}{\Sigma t_{on}} = \frac{100 \cdot \Sigma Q_{out}}{\Sigma Q_{in}} \; (t_{on} \text{ -weighted})$$

$$\bar{t}_R = \frac{100 \cdot \Sigma t_{on}}{\Sigma t_{on} + \Sigma t_{off}}$$

Actual oil nozzle flow rates at the Woodbine and Richard sites were found to be less than the nominal 0.79 ml/s (0.75 gph). This lower input rate would require a higher utilization of the furnaces (i.e., less standby losses) and effectively larger heat exchangers which may be the prime influences for the noteably higher performance at these two sites. The 80.6% performance achieved at the Woodbine site was degraded approximately 2% by soot buildup during the subsequent mistuned operation period, and this factor will be applied to the estimation of season-averaged efficiency.

Although they were identical in construction, differences in efficiency characteristics were noted between field test units, especially below 20% furnace utilization (t_R <0.20). "Dropoff" in performance occurs at low utilization, primarily due to longer periods of standby losses. Part of the function of the inlet air draft flap is to inhibit cooldown of the furnace by restricting free convection through the furnace, thereby maintaining conditions conducive for cleaner starts and reducing standby losses. The path from the firebox to the flue is not mechanically closed, however, and restricted circulation is likely to exist between the heated furnace components and the outdoors via the chimney and sealed-air systems. The effectiveness of the draft control flap assembly is reduced somewhat, and its performance is partly dependent on the individual sites' chimney and sealed-air systems characteristics, resulting in the differences in standby loss characteristics. These individual site characteristics detract from the formulation of a single correlation of furnace efficiency versus utilization for all six integrated furnaces tested.

The effort to correlate cycle-averaged efficiency to cycle-timing parameters was initiated with the formulation of a one-variable, least-squares regression analysis code ("CURFIT") for the Hewlett/Packard controller to evaluate the efficiency data recorded by the H/P 3051A programmable data logger. A listing of the CURFIT code can be found in Appendix A. The parameters are evaluated in six different combinations of transforms, resulting in six forms of curve-fits involving one functional parameter. In addition, the basic form of the parameter can easily be changed, allowing further permutations in the evaluation. The primary influence on cycle-averaged efficiency as opposed to steady-state efficiency (constant value) is the standby loss. This is fairly well represented by t_{on} defining the total amount of heat involved, and by t_{off} defining the period of time that standby loss was permitted. Therefore, a ratio form of these variables was applied, defined as $t_R = t_{on}/(t_{on} + t_{off})$, the furnace utilization factor. Only limited success was achieved when the regression analysis was applied to the entire data set obtained on each furnace unit; however, the results (Appendix E, Table E-1) did indicate that the inverse form of the ratio resulted in the higher values of the index of determination (r^2), thus agreeing with the simplified heat balance analysis described in an earlier section. A simpler form of the time ratio was tried, $t_{R1} = t_{on}/t_{off}$, and the results were erratic, probably due to the expansion of the variable's domain from zero-to-1.0 to zero-to-infinity. It was also deduced that the standby loss is realized in the accounting of heat energy in the following firing cycle when more heat is required for component warm-up for that cycle, so the following off period (t_{off}) parameter was changed to the preceding off period ($t_{off\ j-1}$).

The computer code was expanded to a multiple regression analysis ("MULFIT"), capable of evaluating two-parameter correlations. The two parameters that evolved from the prior heat balance analysis were immediately applied, along with several other forms. The results (Appendix E, Table E-2) showed some improvement by the addition of the t_{on} parameter to the correlation. To estimate the contribution of the t_{on} parameter, it was evaluated alone as the only parameter in the correlation analysis. The analysis of the Pond data resulted in an index of determination approaching zero ($r^2 = 0.0566$), indicating that there may be no correlation of t_{on} to cycle efficiency or at least not to this unrestricted set of data. Although inclusion of the t_{on} parameter appears to improve the index of determination in most cases, it is not clear from the data available nor from the prior single-parameter attempt whether its contribution is a representation of first-order physical realities or if it is simply a mathematical buffer for that range of data. The two-parameter evaluation, however, reinforced the prior analysis of the preceding off-period being the prime influence, with more consistent results obtained from analyses which included this form of the parameter. A firm correlation would need to be established with this prime parameter before attempting to include the apparently secondary influence of the t_{on} parameter, and preferably with a larger data set that includes a wider t_{on} domain.

To pinpoint areas that may mislead the regression analysis, part of the data from each site was plotted. It was learned that abnormally terminated firings (e.g., over-temp control, thermostat changes, etc.) produce erratic results with efficiency values far above (often greater than 100%) and below the basic band of data. Also, data at extremely low utilization periods were found to be erratic and so the analysis was then limited to the domain of interest, typically, $t_R = 0.10$ to 0.90 and $\eta = 60$ to 100%. The results of the evaluations are presented in Table 11, with the letters A and B representing the coefficients derived from the least-squares regression analyses, and r^2 the resultant index of determination for the respective correlations. The values of r^2 are notably higher than the earlier unrestricted analyses. Comparison of the r^2 values in Table 11 show that Correlations 3, 4, and 6 are consistently higher than the other correlations; however, it is not apparent which of the three is the best fit. Statistical confidence intervals were calculated for the index of determination of each site for these three correlations to observe whether the "best" correlation could be identified quantitatively (Analysis 1, Appendix F). The results showed no relative changes, with the resulting three correlations essentially equal statistically. The selection of the "best" correlation would need to consider other factors. It is important to note here that none of the calculated lower limits of the confidence intervals for the index of determination approached zero (see Table F-1, Appendix F). This indicates with 95% surety that a correlation of the timing ratio parameter (t_R) to cycle-averaged efficiency does exist. This is an important confirmation, based on a statistically sizeable sample of actual

TABLE 11

RESULTS OF THE SINGLE-PARAMETER LINEAR REGRESSION ANALYSIS OF CYCLE-AVERAGED EFFICIENCY DATA OBTAINED FROM THE INTEGRATED FURNACE UNITS IN THE 1977-1978 FIELD TEST

Form of Correlation \ Site		Woodbine	Richard	Pond	Gravon	Stovepipe	Fissette
$\eta = 100\cdot(A+B.t_R)$	A	.6595	.6538	.6132	.6517	.6786	.6998
	B	.64080	.35135	.32403	.18675	.26331	.19352
	r^2	.5683	.5496	.5293	.8143	.6912	.6237
$\eta = 100\cdot A\cdot e^{Bt_R}$	A	.6655	.6583	.6191	.6551	.6819	.7013
	B	.82055	.46921	.45068	.25060	.34413	.25545
	r^2	.5526	.5449	.5068	.7941	.6591	.6051
$\eta = 100\cdot A\cdot t_R^{B}$	A	1.1269	.9211	.8773	.8211	.8908	.8520
	B	.22408	.15702	.17451	.10894	.11771	.085350
	r^2	.7026	.6358	.6031	.8306	.8219	.7728
$\eta = 100\cdot\left(A + \frac{B}{t_R}\right)$	A	.9937	.8722	.8470	.8199	.8379	.8126
	B	-.03941	-.03098	-.03835	-.02531	-.01886	-.01317
	r^2	.8083	.6442	.6398	.7800	.8089	.7570
$\eta = \frac{100}{A + B\cdot t_R}$	A	1.4926	1.5110	1.603	1.5198	1.4605	1.4231
	B	-1.0575	-.6295	-.6306	-.3372	-.4514	-.3377
	r^2	.5339	.5353	.4779	.7722	.6262	.5862
$\eta = 100\cdot\frac{t_R}{B + A\cdot t_R}$	A	.9333	1.1120	1.1378	1.2110	1.1757	1.2215
	B	.06680	.05777	.07819	.04681	.034365	.02382
	r^2	.8006	.6798	.6341	.7857	.8283	.7651

where

$$t_R = \frac{t_{on}}{t_{on} + t_{off\ j-1}} \text{ (limited to 0.10 - 0.90)}$$

η = cycle-averaged efficiency (limited to 60 - 100%)

test data, of the characterization of the standby heat loss effect that has thus far been the result of only analytical evaluations.

The representative curves were generated from the three correlations and plotted along with the respective sites' data for visual evaluation. It was immediately apparent that the power function represented by Correlation 3 was not characteristic of the trend described by the data, whereas Correlations 4 and 6 both appeared to fit the data equally well. The heat loss analysis discussed in a previous section indicated that the reciprocal of the cycle timing ratio describes the standby loss; thus, Correlation 4 is the preferred form and, therefore, was selected over Correlation 6. The cycle-averaged efficiency data plots used to visually verify the curve-fits (Correlation 4) are presented in Figures 16 through 21. These plots represent only part of the total data set, where only enough data points to represent a wide range of timing ratios (t_R) were plotted so the data trends would be more apparent and not obscured by a mass of points near the mean timing ratio. Also shown on these plots are the respective curves of Correlation 4 ($\eta = f(1/t_R)$, Table 8). The correlations generally fit well through the bulk of the data, but most require correction above $t_R = 0.50$ due to the relatively small number of firings recorded at furnace utilization greater than 50% ($t_R > 0.50$). The steady-state heat losses are proportional to firing duration, and the correction required at the higher timing ratios may be the increasing influence of this factor (t_{on}). The few points at the higher t_R values, however, are orderly and appear reasonable in their approach toward the steady state efficiency value ($\eta_{ss} \approx 85\%$), so the correction required is well defined and can be applied with a high degree of confidence. This would allow the application of the one-parameter correlation to extend beyond the monitored period into periods of higher heating demands (i.e., higher t_R's).

A distinct difference in cycle-averaged efficiency characteristics can be noted between the Boston (Figures 16 through 18) and the Albany (Figures 19 through 21) units. Woodbine, Richard, and Pond data all show steeper dropoffs in efficiency with low furnace utilization than that seen in the data from Gravon, Stovepipe, and Fissette sites. The cause of these differences is not apparent, but all three Albany sites are one-story structures (i.e., shorter chimneys) and the standby draft potential is, therefore less, presumably resulting in less losses.

1978-79 Cycle-Averaged Efficiency Results – During the first heating season, the output efficiency measurements were obtained with one computer-controlled data logger system, which was then supplemented by an additional system in the second heating season. Although the number of monitoring visits was reduced by 33%, the amount of output efficiency data obtained during the second season was nearly doubled.

The results obtained during the second season of testing are generally the same as the first with shifts in the data at some of the sites, probably caused by variation in the flow rate characteristics of the oil nozzles which were replaced between heating seasons. The range of furnace utilization levels over which data were recorded increased notably in the second period

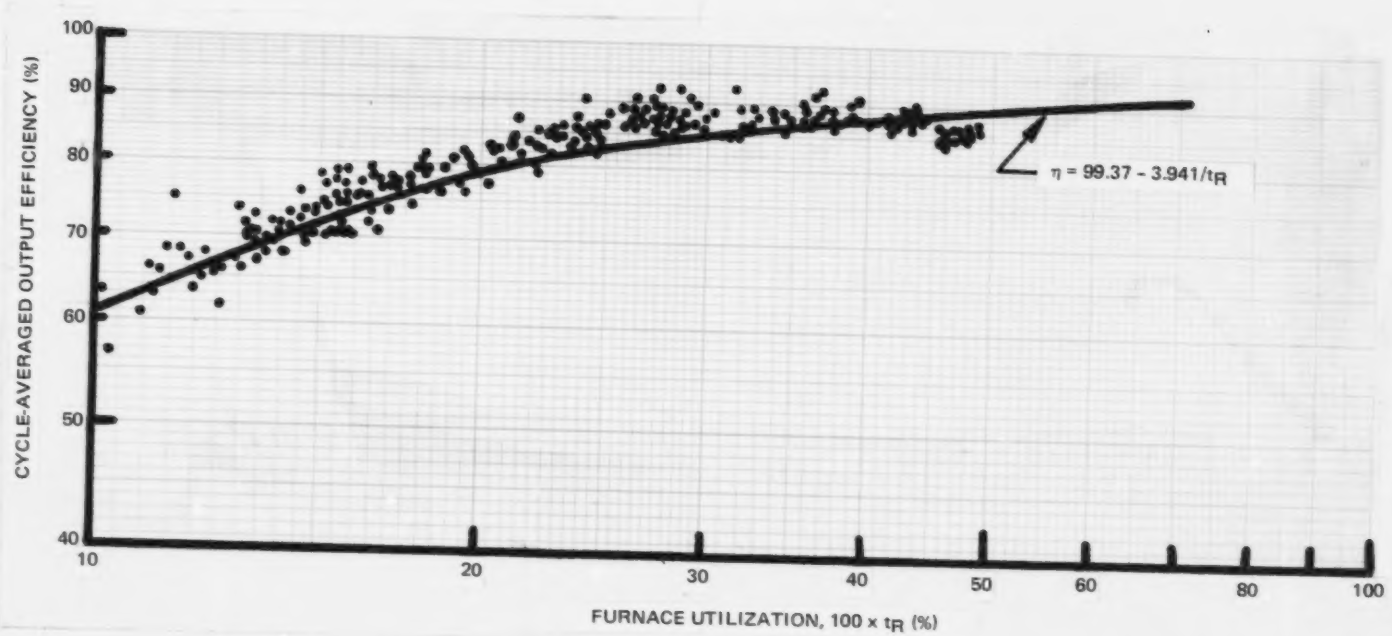

Figure 16. Integrated Furnace Performance vs Utilization for Unit 5 Installed at the Woodbine Site in the Boston Area During 1977-1978

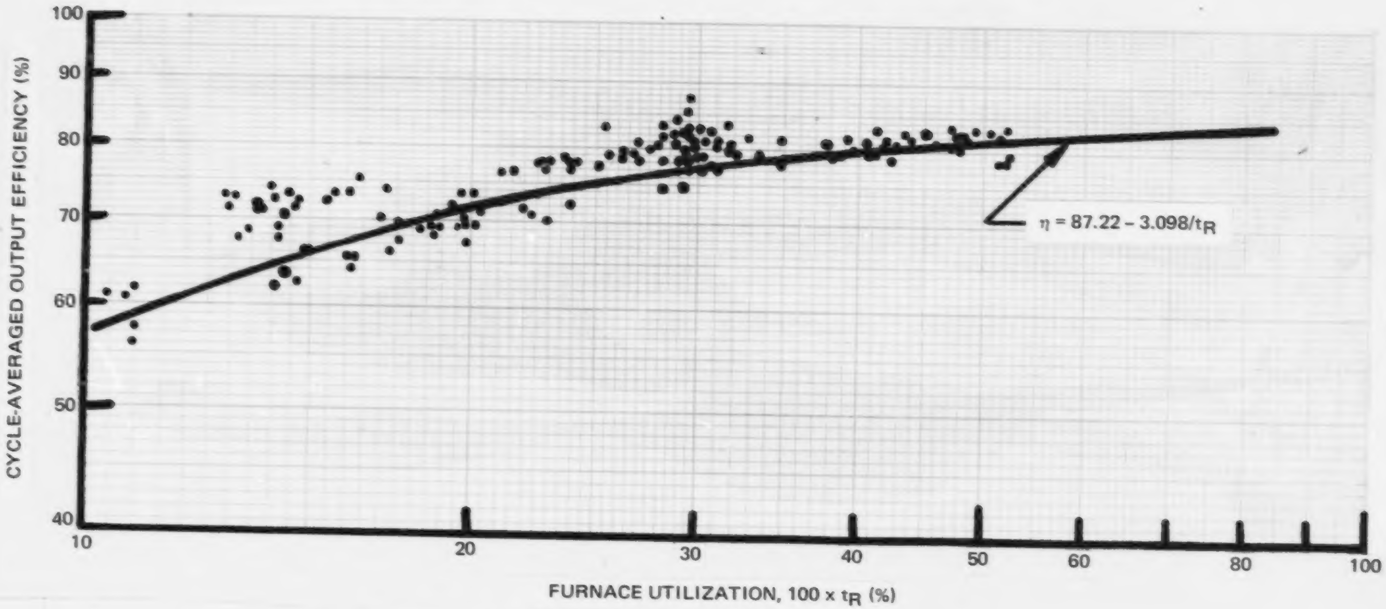

Figure 17. Integrated Furnace Performance vs Utilization for Unit 4 at the Richard Site in the Boston Area During 1977-1978

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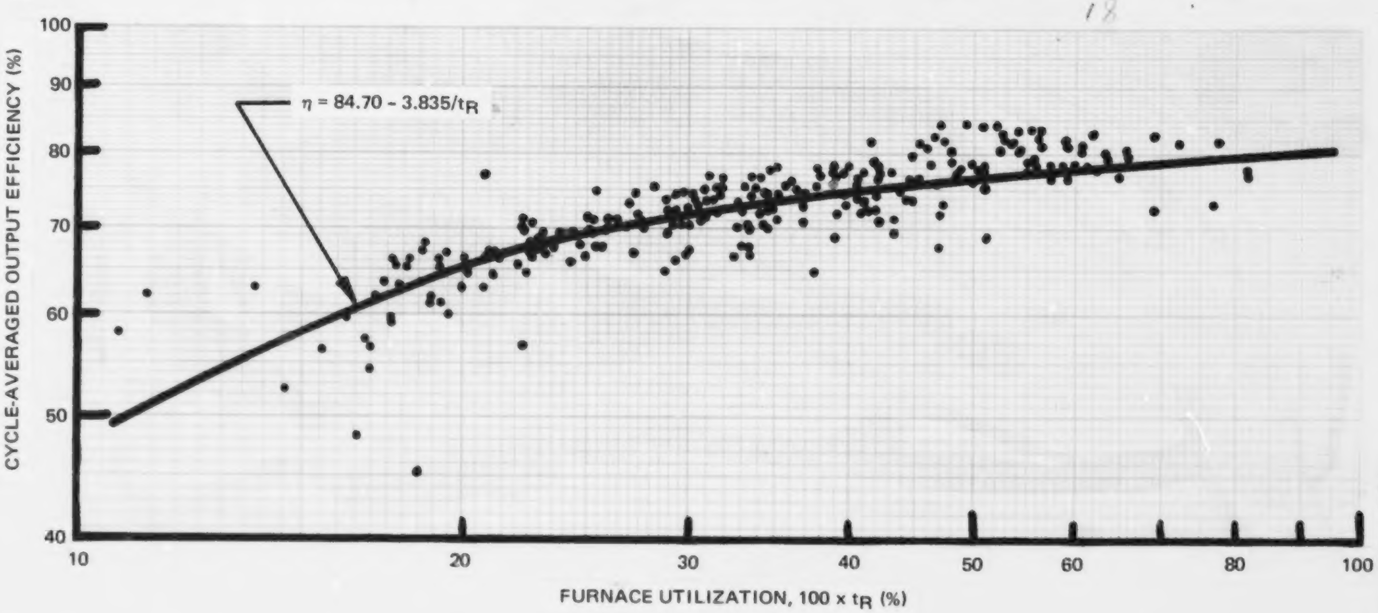

Figure 18. Integrated Furnace Performance vs Utilization for Unit 1 Installed at the Pond Site in the Boston Area During 1977-1978

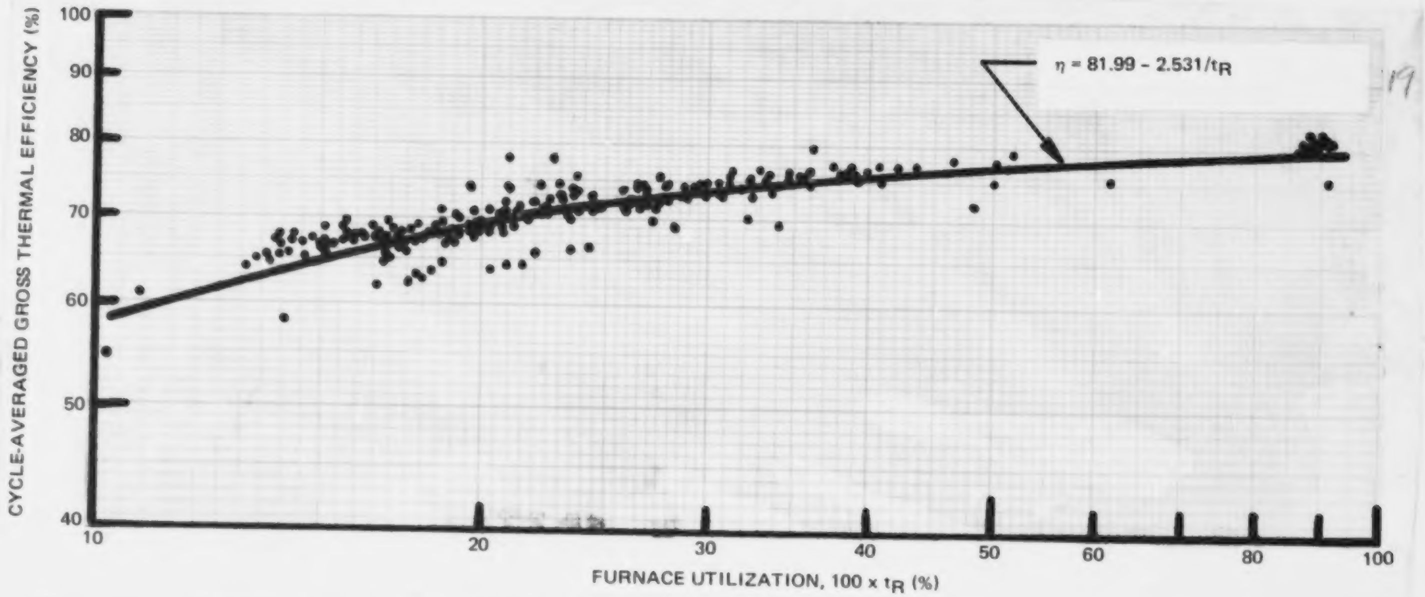

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Figure 19. Integrated Furnace Performance vs Utilization for Unit 2 Installed at the Gravon Site in the Albany Area During 1977-1978

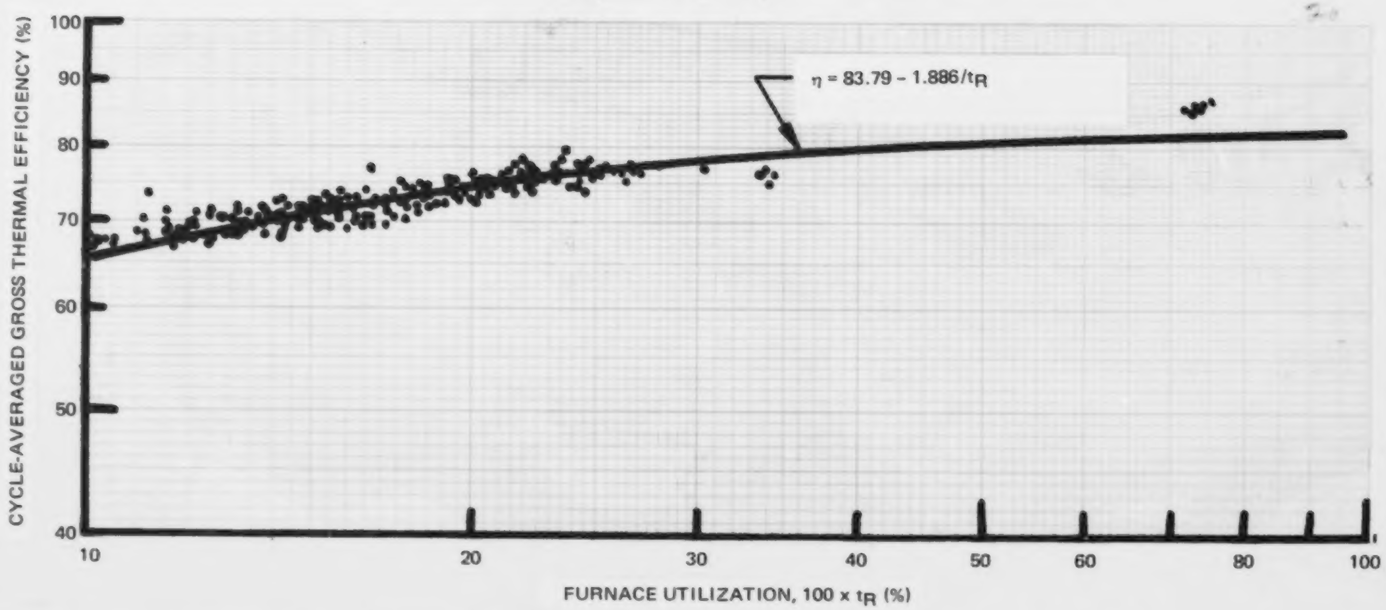

Figure 20. Integrated Furnace Performance vs Utilization for Unit 6 Installed at the Stovepipe Site in the Albany Area During 1977-1978

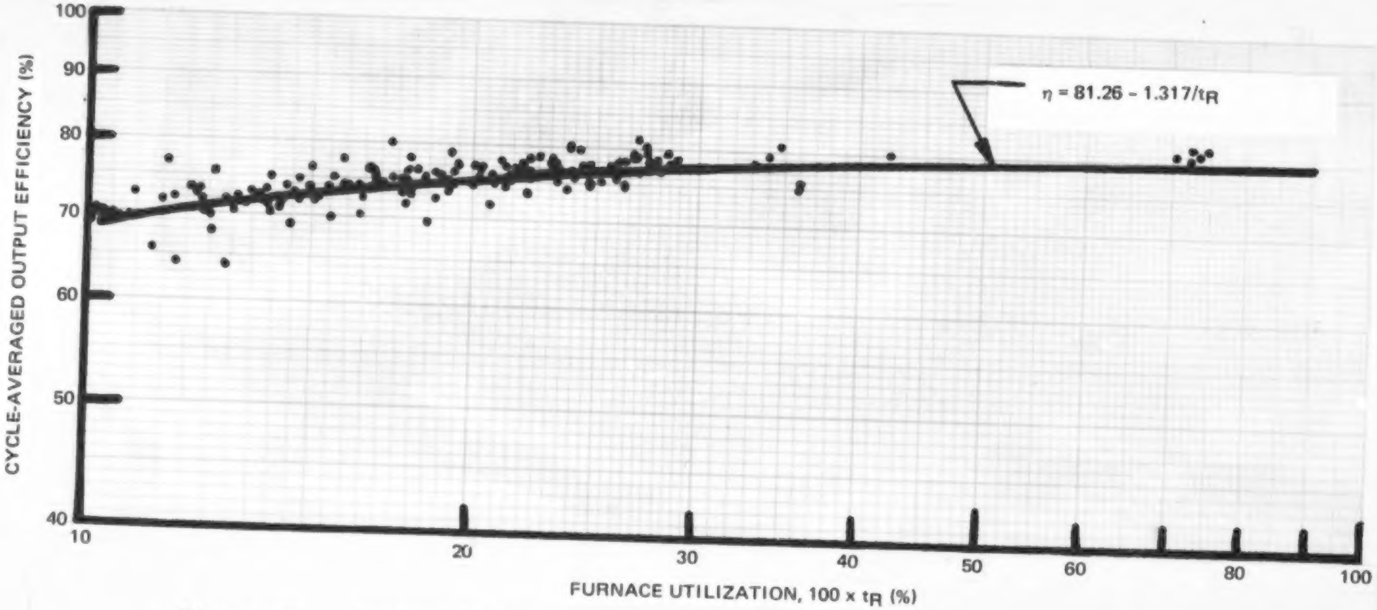

Figure 21. Integrated Furnace Performance vs Utilization for Unit 3 Installed at the Fissette Site in the Albany Area During 1977-1978

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because of the addition of a second programmable data logger that allowed longer monitoring periods at each site. This, of course, presented a better definition of the furnace output efficiency characteristics.

The output efficiency data versus furnace utilization are presented in Figures 22, 23, and 24 for the Boston-area sites and Figures 25, 26, and 27 for the Albany-area sites. The Woodbine site data in Figure 22 again show an apparent peak in the efficiency curve, as was seen in the prior season's data. This season, however, it appears at about 40% utilization as opposed to about 28% last season. The bulk of the data in the area of the "peak" falls in line with the general trend of the data, and the peak is formed by data points falling along the upper edge of the scatter band. The peak is probably caused by a "quirk" in the coupled fan thermostat/heat storage characteristics.

The overall performance of the Woodbine furnace is generally lower than the prior season. This may be attributed to a combination of factors. The actual firing rate is higher (i.e., lower equivalent heat transfer surface area), and the furnace was inadvertently run at lower than design stoichiometric ratio conditions in 1977-78, which promoted accumulation of soot in the heat exchanger.

The Richard site data (see Figure 23) also show slightly lower overall performance than the prior season's performance. This unit also experienced conditions similar to Woodbine site, and the shift in performance was probably influenced by the same factors.

The Pond site data (Figure 24) show nearly identical performance to the prior season's results. The large amount of data scatter at this installation, however, allows a greater tolerance in the visual comparison and complicates the statistical evaluation as will be discussed later in this section.

The Albany-area sites performed relatively unchanged from the previous season's performance. The results from the Gravon site (see Figure 25) show no significant changes in performance characteristics from last season's results (Figure 19). The span of furnace utilization is measured more fully, with no notable deviations from the general trend.

Data from the Stovepipe site (Figure 26) are an overlay of last season's data, matching in both magnitude and trend. The data scatter in the efficiency performance results from this unit is minimal, the lowest of all six test furnaces. The cause and significance of the differing degrees of data scatter will be discussed later in the section. The data were acquired at this site during the midwinter months of December through January, and the 35% utilization rate data points shown on the graph represent the maximum furnace utilization.

The Fissette site was monitored from September into December 1978, which represented a wide spectrum of utilization compared to the last two months in the previous heating season. The data, however, confirm the general magnitude and trend of the results acquired in the previous season. The performance

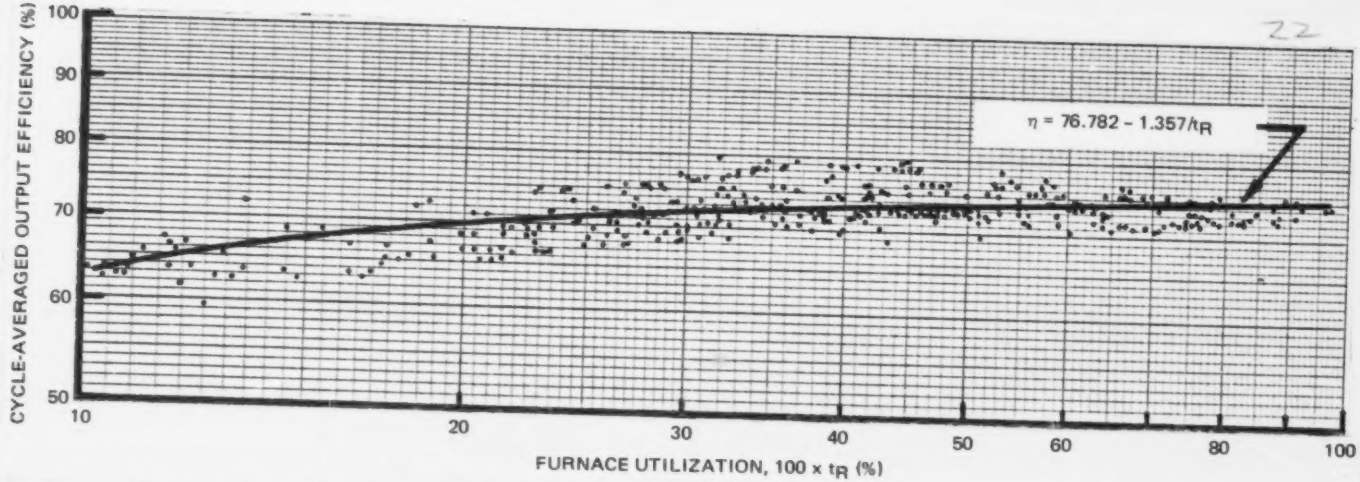

Figure 22. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 5 Installed at the Woodbine Site in the Boston Area During 1978-1979

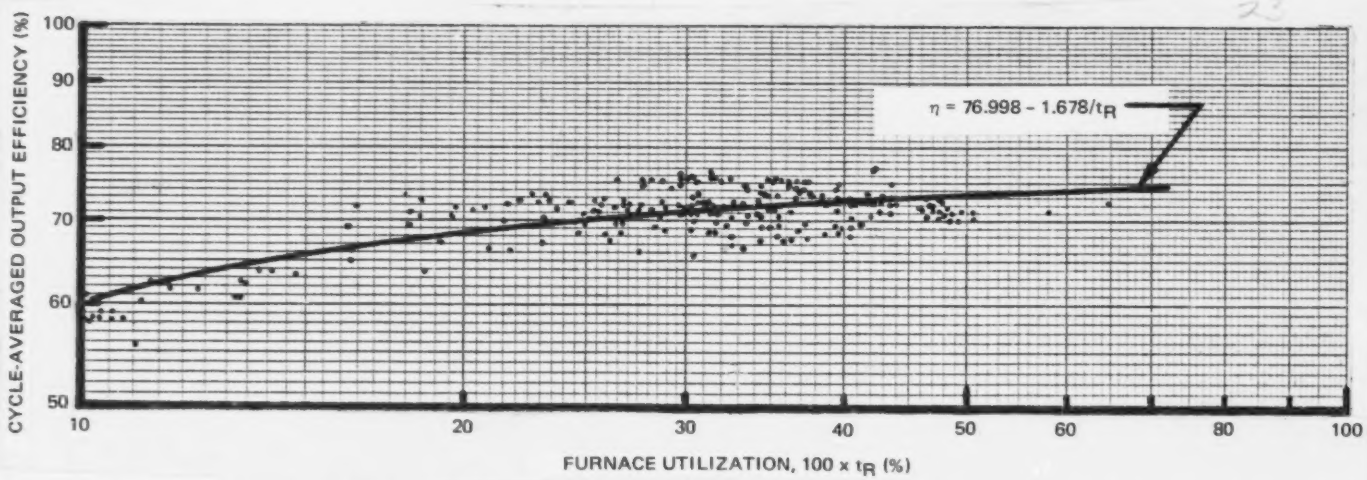

Figure 23. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 4 Installed at the Richard Site in the Boston Area During 1978-1979

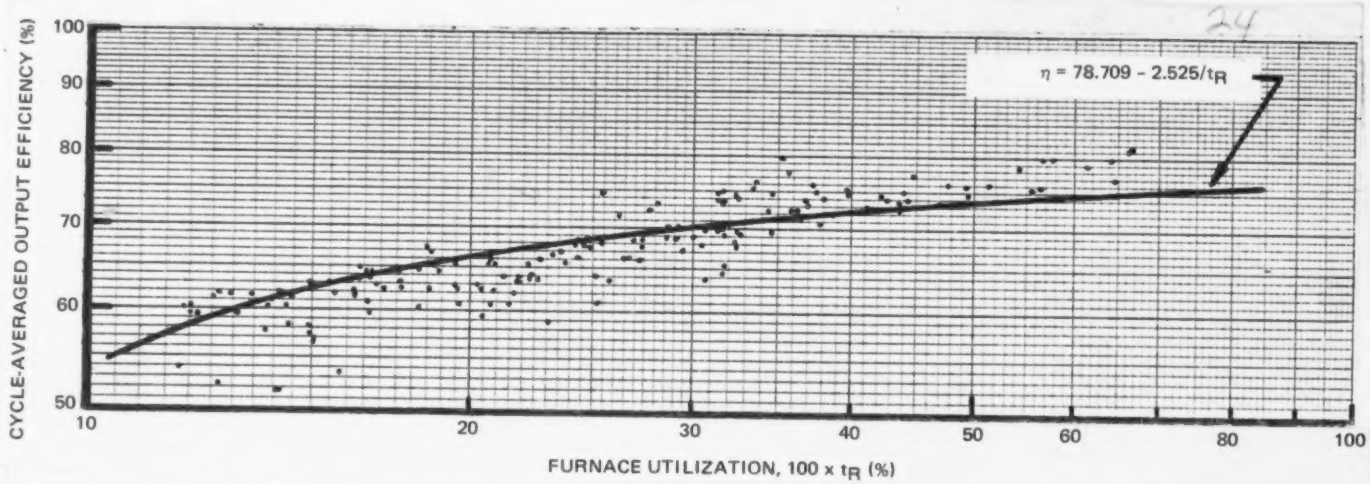

Figure 24. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 1 Installed at the Pond Site in the Boston Area During 1978-1979

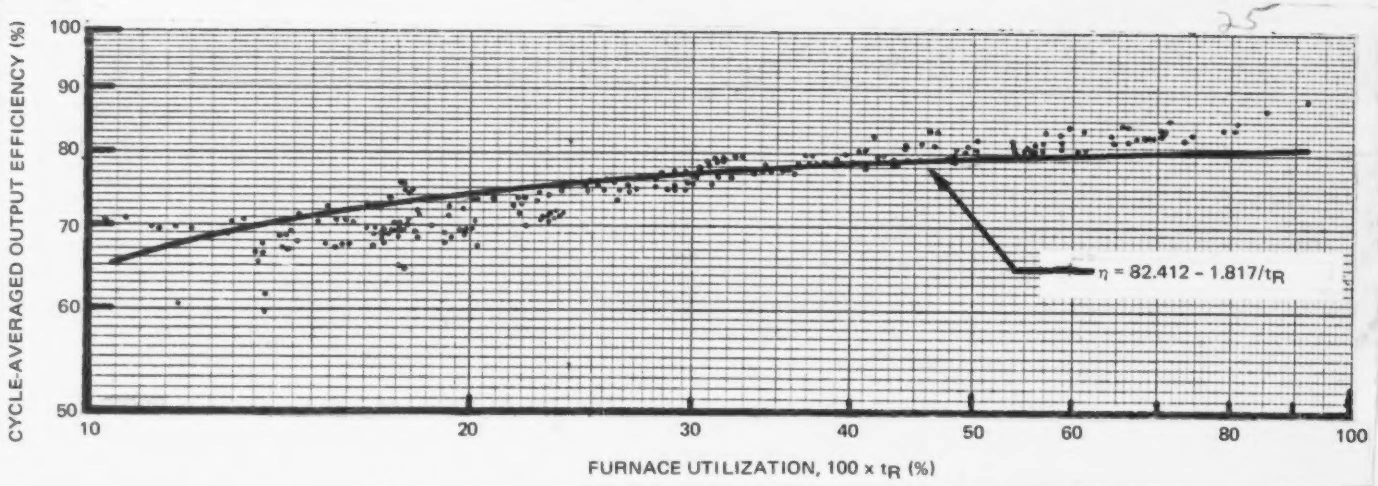

Figure 25. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 2 Installed at the Gravon Site in the Albany Area During 1978-1979

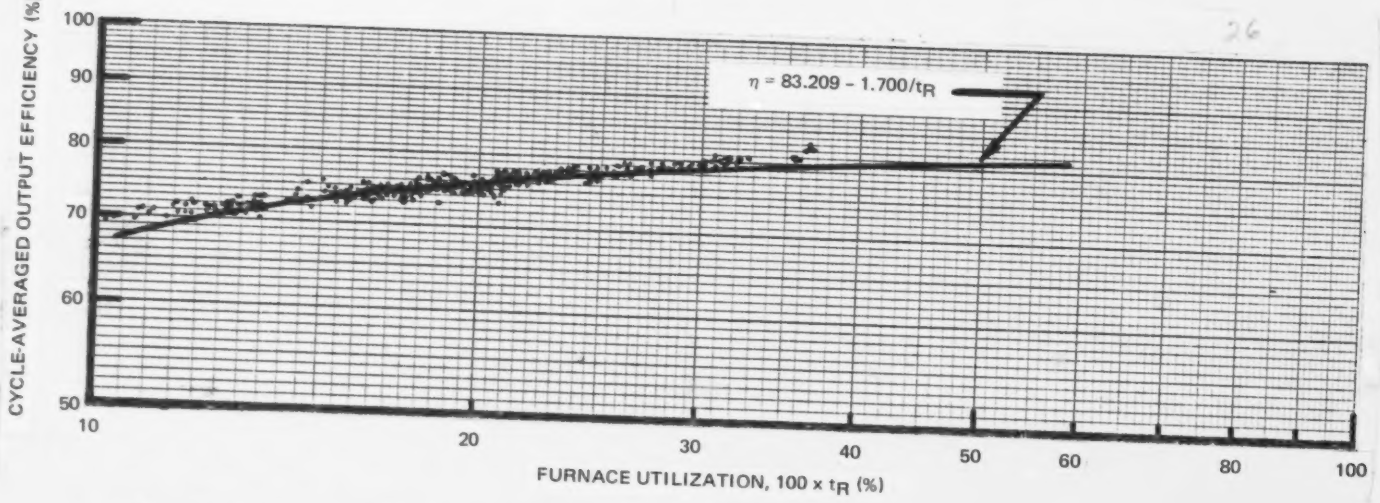

Figure 26. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 6 Installed at the Stovepipe Site in the Albany Area During 1978-1979

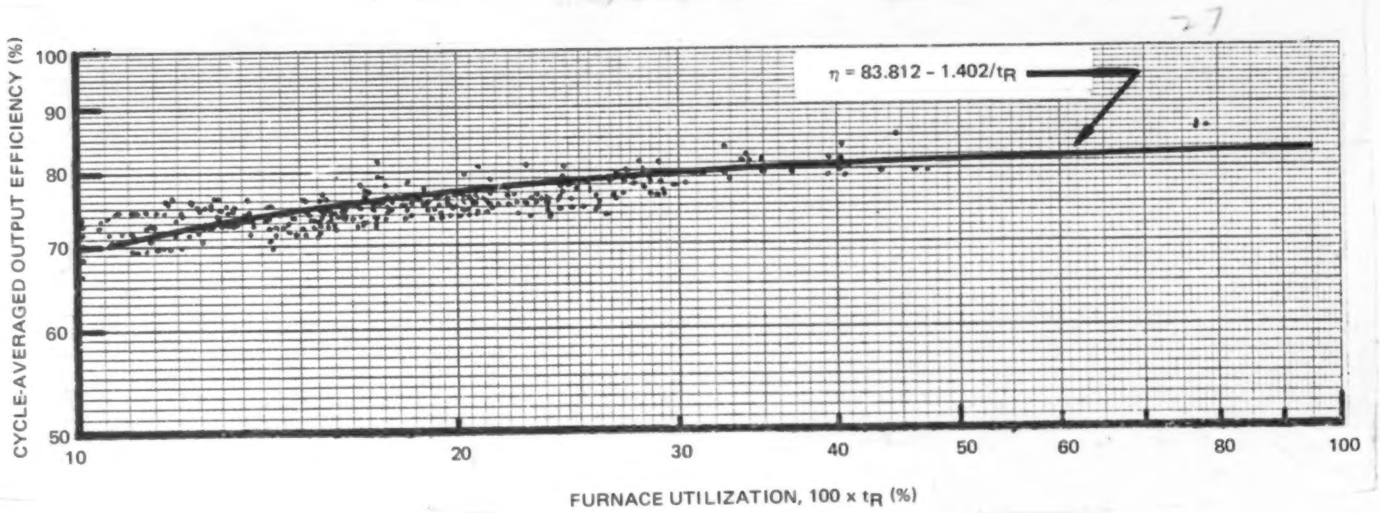

Figure 27. Integrated Furnace Measured Efficiency Performance vs Utilization for Unit 3 Installed at the Fissette Site in the Albany Area During 1978-1979

characteristics are very similar to the Stovepipe installations, showing a relatively slow rate of dropoff in performance with lower utilization.

The least-squares curve-fit evaluation of the 1978-79 efficiency data produced essentially the same general conclusions as the 1977-78 data. The two-parameter correlations generally resulted in a slightly higher index of determination, but the coefficients of the second test period were not consistent and often did not appear to represent a real phenomenon. Many of the two-parameter correlations were nearly overlays of the selected single-parameter correlations. The inverse function of furnace utilization again appeared to best represent the cyclical operation efficiency performance characteristics of the integrated furnaces.

The performance data from the Boston sites generally have a higher degree of "scatter" than the Albany data. This was originally thought to be influenced by conditions in the flue, but subsequent laboratory tests showed it to be inconsistencies in the operation of the fan control component within the furnace (see Supplementary Laboratory Tests section). So the amount of scatter is basically an indication of the operation of one electrical component and not an indication of erratic performance of the furnace or the monitoring system. It does, however, complicate the statistical evaluation procedure because the scatter will increase the total deviation from any characteristic curve, thus affecting the least-squares difference analysis. Comparison of the Boston-area data (Figures 22-24) against the Albany-area data shows the effect of the greater scatter upon the resulting correlations. The wide data bands allow high degree of latitude in visual fitting of correlation curves. The Woodbine data (Figure 22) between 10 and 45% utilization indicate a steeper slope and a higher intercept at 100% (steady state). The Richard data (Figure 23) are inadequate above 50% utilization for an extrapolation to steady state. The Pond data also have only a small percentage of its points above 50% utilization and none over 65%, leaving the extrapolation to a steady-state efficiency performance value a little weak; however, visual indications appear to be between 80 to 85% efficiency. To counter these inadequacies, the sample size was increased by lumping data from both test periods and all three sites in each area.

Table 12 permits a comparison of the resultant correlation coefficients for both the 1977-78 and 1978-79 heating season data. The 1978-1979 data again showed a marked difference in performance between the Boston and Albany furnace installations. Additionally, the Boston sites' correlations differ significantly between the results and the two seasons. The 1977-78 correlations for Woodbine and Richard sites were based on data sets that were interrupted by occasional periods of off-design conditions operation, which may be the primary factor in the change in the coefficients.

The Pond data from the two seasons were visually identical; however, significant differences in the resultant least-squares coefficients are shown in Table 12. The data scatter in the Pond data is about the highest of all six sites, and this, coupled with changes in the distribution of the data, may have influenced the formulation of the correlation coefficients. Since the

TABLE 12

COMPARISON OF CURVE-FIT CORRELATION COEFFICIENTS GENERATED FROM LEAST-SQUARES REGRESSION ANALYSIS ON THE FIELD TEST OUTPUT EFFICIENCY DATA

Site	1977-78 Results		1978-79 Results	
	Coefficients		Coefficients	
	A	B	A	B
Woodbine	99.37	-3.94	76.78	-1.36
Richard	87.22	-3.10	77.00	-1.68
Pond	84.70	-3.84	78.71	-2.53
Boston Sites (1977-79 Comb.)	——	——	81.91	-3.11
Gravon	81.99	-2.53	82.41	-1.82
Stovepipe	83.79	-1.89	83.21	-1.70
Fissette	81.26	-1.32	83.81	-1.40
Albany Sites (1977-79 Comb.)	——	——	81.14	-1.46

$$\eta_{cyc} = A + B/t_R$$

where

$t_R = t_{on}/(t_{on} + t_{off})$

t_{on} = burner-on time

t_{off} = preceding standby period

data plots appear more closely matched than the differences in the coefficients indicate, the combined 1977-78 and 1978-79 data sets were evaluated. The results showed an improvement in the index of determination from 0.643 and 0.561, separately, to 0.693 for the combined analysis. The coefficients (see Table 12) are also more in line with the results of the Albany data.

The least-squares curve-fit analyses of the Albany-area data produced a very consistent set of correlations, both with the prior season's correlations and between the three sites, as seen in Table 12. Additionally, the nominal magnitudes of the correlations appear physically realistic, approaching values of about 80% efficiency at steady state which are in general agreement with the 83 to 84% level of performance determined by the flue gas heat loss method (including two percentage points assumed cabinet heat loss). These results revive possibilities of a "universal" characteristic efficiency performance curve for the integrated furnace system. To investigate this, all the efficiency data from the Albany-area sites, from both test periods, were included in a least-squares analysis. The resulting coefficients are also shown in Table 12. The calculated index of determination for the curve-fit is 0.564, which is approximately the mean of the individual results. The "A" coefficient, surprisingly, turns out lower than any of the individual coefficients, thus resulting in a calculated steady-state performance of 79.7%.

Estimate of Season-Averaged Efficiency — Each individual site's efficiency performance correlation was applied to the cycle timing data for other periods of the heating season to derive an estimate of overall performance of the integrated furnaces.

The correlations used to determine the 1977-78 season-averaged performance were the one-parameter function using the inverse of the furnace utilization ratio ($\eta = A + B/t_R$, Correlation 4, Table 11) up to $t_R = 0.40$. A power function ($\eta = A \cdot t_R^B$) was used to represent the efficiency characteristics in the higher utilization region. The application of a second function to describe the higher utilization region has been used here simply because it provides an improvement of accuracy to the estimation of season performance since very little efficiency data above $t_R = 0.40$ were recorded, causing the primary correlations to be inaccurate in that region. As mentioned in the preceding section, the longer (i.e., higher t_R) firings may require inclusion of a firing time (t_{on}) parameter to describe the increasing contribution of steady-state losses.

The expanded efficiency monitoring effort (two programmable data loggers) in the second field test heating season provided significantly more data from each test installation. This resulted in efficiency correlations being applicable over greater spans of utilization. Therefore, the estimates of season-averaged performance during the 1978-79 heating season were generated using only the respective inverse utilization correlations (shown on the data plots and in Table 13).

TABLE 13

SUMMARY OF ESTIMATED SEASON-AVERAGED THERMAL EFFICIENCY PERFORMANCE OF THE INTEGRATED FURNACES

Furnace Test Site	1977-78 Heating Season*			1978-79 Heating Season		
	Average Furnace Usage (t_R, %)	Average Burner-On Time (min)	Estimated Season Efficiency (%)	Average Furnace Usage (t_R, %)	Average Burner-On Time (min)	Estimated season Season (%)
Woodbine Street MA (Unit 5)	42.4	12.8	(81.0)**	38.8	13.94	71.8
Richard Road MA (Unit 4)	44.7	13.3	(79.3)**	22.1	9.16	70.8
Pond Avenue MA (Unit 1)	30.0	5.7	70.4	33.5	8.80	70.2
Gravon Road NY (Unit 2)	21.2	11.0	69.7	28.4	15.10	75.6
Stovepipe Road NY (Unit 6)	30.7	10.2	77.2	28.4	8.76	76.1
Fissette Drive NY (Unit 3)	31.3	10.8	75.8	22.0	6.78	76.3
Overall Averages	33.4	10.6	73.3 (75.6)	28.9	10.4	73.5

*No timing data available for September and October 1977

**Incomplete timing data, recorder malfunction

The results from the evaluation of the cycle timing data are presented in Table 13 for both test periods. The season efficiency is the t_{on}-weighted average efficiency derived from applying the above correlations and weighing each firing by the amount of heat involved, represented by the burner-on time. The measured efficiency data, acquired by the programmable data loggers, were proportionally combined with the calculated efficiency results based on the timing information to account for the entire monitored periods, and the resultant values are expressed as "season-averaged" efficiencies. Note that the 1977-78 estimates exclude September and October of 1977, since no timing data loggers were operational at that time. These low utilization months may influence the resultant season estimated values downward by perhaps 1% to 2%. Additionally, problems with the cycle timing data loggers were encountered at Woodbine and Richard sites so these incomplete projections are denoted in parentheses. The overall average estimated "season-averaged" efficiency for the 1977-78 test period, excluding the Woodbine and Richard (half season) data, is 73.3%; inclusion of these sites' data increases it to 75.6%.

The results of the 1978-79 heating season are based on complete data records available for all the sites, with no recorder malfunctions encountered. The resultant estimates of season-averaged performance vary from 70 to 76%. Overall agreement between the sites are relatively good; however, a distinction between the Boston and Albany sites can be seen. The average performance for the integrated furnaces during the 1978-79 heating season is 73.5%, about 10 percentage points lower than steady-state performance. This is in close agreement with the prior test season's average of 73.3%.

Fuel Utilization Comparison — The only comparison to the prior furnace systems is in the comparison of previous fuel utilization histories to those recorded with the integrated furnaces during the field test. The occupants were instructed to maintain thermostat temperature settings and dwelling use patterns as close as possible to the prior two seasons in an attempt to leave weather as the only significant variable. To correct for the differences in weather, degree-day information generally used in the heating industry to estimate fuel consumption was recorded along with the amount of fuel consumed. The amounts of fuel consumed in each period are normalized by the respective weather factors, and these are the values used for comparisons. These data are presented in Table 14 for both the original furnace and the integrated furnace service periods. The changes in fuel utilization brought about by the integrated furnaces are notable, showing reductions in all cases, ranging within a 95% confidence band of 10.7 to 19.5% and averaging 15.7%. The wide band of net change values is caused by the wide variety of original furnaces being compared, from some inconsistencies that exist in the prior fuel history data, and variations in the host's ability to maintain constant heating demand over the 4-year period involved.

The prior fuel utilization data are based solely on old delivery records from several suppliers and include inaccuracies caused by partial fuel deliveries as well as variations in the dwelling usage (vacations, fireplace use, thermostat setback, etc.). This can be seen in the year-to-year variations of gallon/degree-day seen in Table 14.

TABLE 14

EFFECT OF INTEGRATED FURNACE ON FUEL OIL CONSUMPTION

Test Site	Consumption History			Integrated Furnace Field Test			
	1975-1976 (gal/D-D*)	1976-1977 (gal/D-D*)	2-Season Average (gal/D-D*)	1977-1978 Test Period (gal/D-D*)	1978-1979 Test Period (gal/D-D*)	2-Season Average (gal/D-D*)	Net Improvement (%)
Woodbine Street Newton, MA Unit 5	0.2888	0.2794	0.2837	0.2383	0.2184	0.2284	19.49
Richard Road Needhan, MA Unit 4	0.1306	0.1250	0.1276	0.1061	0.1029	0.1045	18.10
Pond Avenue Brookline, MA Unit 1	0.1322	0.1176	0.1244	0.1114	0.1088	0.1101	11.50
Gravon Drive Delmar, NY Unit 2	0.0932	0.0848	0.0890	0.0717	0.0847	0.0782	12.13
Stovepipe Road Clarksville, NY Unit 6	0.0970	0.0935	0.0953	0.0776	0.0716	0.0746	21.72
Fissette Drive Feura Bush, NY Unit 3	0.0937	0.0811	0.0871	0.0791	0.0758	0.0775	11.05
						Overall Average	15.67

*Degree-Day, ^{o}F-Day (Reference temperature: MA = 65^{o}F, NY = 70^{o}F)

Analysis of this fuel use variability has indicated that the year-to-year variations in four of the six residences are large enough to preclude an absolute comparison of pre- and post-integrated furnace fuel consumption at each site. The average of all six sites, however, should represent at least an order-of-magnitude indication of the improvements in fuel utilization with the use of the integrated furnace system.

The overall average improvement in fuel utilization is 15.7%, and this is in general agreement with furnace performance studies by other investigators (References 8 and 9). The 73.4% estimated season-averaged thermal efficiency from the integrated furnaces and the resultant 15.7% improvement in fuel utilization seem to correspond to the mean season-averaged thermal efficiency range of the original furnaces suggested by the data obtained by Turner (Reference 10).

Thermal Efficiency Performance

While the fuel utilization comparison showed a 15.7% improvement with the integrated furnace, an exact value of improvement in gross thermal efficiency is difficult to extract from the data available. Although the cycle-averaged thermal efficiency performance is well documented for the integrated furnace, similar data for typical furnaces are not available for direct comparisons of furnace efficiency performance. The comparison of the extrapolated season-average efficiency against the improvement in fuel utilization is not directly applicable because of the sealed-air system which changes the dwelling infiltration characteristics, which directly affects utilization, but only indirectly affects furnace efficiency. Peoples (Reference 9) predicted the effect of the sealed-air system upon fuel utilization may be from 5 to 10%, which, when compared to the 15.7% gain in fuel utilization, indicates that the net improvement in gross thermal efficiency is on the order of 10 to 5%. There are also minor differences in the field test and the research furnace (Reference 9) configurations that may influence these values. The integrated furnace, by virtue of its sealed burner vestibule design, preheats the combustion air in the vestibule where combustion air inlet temperatures from 10 to 18°C (50 to 65°F) have been measured, depending on the outdoor temperatures. This partial preheating reduces the effect of the sealed-air system upon fuel utilization by perhaps as much as two percentage points. Also, the higher predicted value of improvement in fuel utilization was based on the consumption of fully heated living-space air (70°F, 30% relative humidity), which was not the case for any of the installations. The furnaces were located in primarily utility areas, maintained well below the living space temperature. Additionally, all of the sites maintained thermostat settings no higher than 20°C (68°F). Using a value of 17.2°C (63°F) for furnace space air and accounting for reduced effectiveness of the preheated combustion air segment, the estimated improvement from the sealed-air system at 35% furnace utilization is 5.4%, using data provided in Reference 4. This lower estimate of the contribution of the sealed system means that the contribution from increased gross efficiency is greater, very close to the ten percentage points goal established for the integrated furnace field test.

Varying degrees of corrosion were noted in the barometric flue damper at all of the sites, induced by partial condensation of the flue gas products which formed dilute acid (primarily sulfuric) solutions. Analysis of residue found in the damper assembly revealed it to be zinc sulfate hexahydrate, a product of a reaction of the zinc galvanizing and a sulfur agent. This condition was promoted by the relatively low bulk temperature of the flue gas (i.e., high efficiency) from the integrated furnace, and a convection loop formed by the cold, outside air intake system coupled with the warm flue system. The low flue gas temperature, 150° to 175°C (302° to 347°F), is 50° to 70°C closer to the condensation limit than most of the residential furnaces presently available, and this obviously creates a condition more conducive to condensation in the flue pipe. The primary contributor, however, is believed to be the natural convection circulation loop formed by the open cold intake air duct of the sealed-air system connected to the warm flue at the barometric damper plenum. The weighted damper inhibits free circulation somewhat, but it has been observed in the field to be pushed open during burner-off period by the natural convection forces. A flue closure device was considered during the design evaluation phase; however, at that time commercial approval of such a device for oil-fired furnaces in the near future appeared unlikely and, therefore, an inlet closure design was selected. Since then, flue closure devices have been approved, and a double butterfly valve (on a common shaft) design, which would close both the flue and the intake pipes, could be adapted to the integrated furnace system, thereby resolving the flue corrosion problem.

NBS Estimated Seasonal Performance

The National Bureau of Standards Furnace Seasonal Performance Procedure (Reference 11) is a laboratory-oriented procedure devised to be conducted on new furnaces in a laboratory. Laboratory tests on two of the integrated furnaces were subsequently conducted; however, the procedure was also conducted at the field installations before removal. This was conducted to investigate the effect of real conditions (e.g., flue height >1.5 m) upon the results of the rating procedure.

The NBS procedure was performed in the field at the Pond and Gravon sites (Units 1 and 2). The standby draft loss restrictor system on the integrated furnace system (inlet closure) differs from the typical configuration (outlet closure), so the NBS procedure was run twice on each unit, once with the closure system in the normal mode, then again with the closure system deactivated to obtain comparisons. The results from the two sites are presented in Table 15, showing both the normal mode and the "no draft restrictor" mode. The standby draft restrictor system has no effect on the burner-on mode so the steady-state efficiencies are unaffected, and they agree with early results obtained on the integrated furnace system, which were on the order of 84%.

The estimates of efficiency performance in cyclical operation over the entire season, however, differ significantly from the measured (Rockwell/EPA method) efficiency data. Table 15 shows that in both cases, cyclical operation resulted in higher estimated efficiency performances than the steady-state mode, a condition which at these high values (near maximum achievable

TABLE 15

RESULTS OF THE NBS FURNACE RATING PROCEDURE FOR THE POND AND GRAVON FIELD INSTALLATIONS

System / Heat Loss	Pond		Gravon	
	Integrated System	No Draft Flap	Integrated Furnace	No Draft Flap
Steady-State[(7,11)]				
Latent Heat Loss	-6.50	-6.50	-6.50	-6.50
Sensible Heat Loss	-9.90	-9.90	-9.20	-9.20
η_{SS}	83.60	83.60	84.30	84.30
Cyclical[(11)]				
Latent Heat Loss	-6.50	-6.50	-6.50	-6.50
Sensible Heat Loss				
On	-7.50	-7.52	-6.27	-6.28
Off	-0.10	-4.13	-0.11	-4.85
η^*_{NBS} Seasonal	85.90	81.85	87.12	82.37
$\bar{\eta}_{ft}^{**}$ (Rockwell/EPA)	67.5 (70.2)†		75.2 (75.6)†	

$^*\eta_{NBS}$ = Fuel Utilization Efficiency - Seasonal Efficiency (no pilot flame) (@ t_{on} = 3.87 and t_{off} = 13.30)

$^{**}\eta_{ft}$ = Measured Output Efficiency - Field Test Data (@ t_R = 0.2254 (Corr. 4))

†( ) = Rockwell/EPA estimated season efficiency

for noncondensing flue furnace systems) seems unrealistic. In comparison, the respective measured Rockwell/EPA efficiency data for each furnace at the prescribed statistical average utilization level of 22.5% (NBS: t_{on} = 3.87 and t_{off} = 13.30 minutes) are significantly lower, by 14 to 20%. The lower on-time sensible heat loss in the cyclical mode is caused by heat storage in the furnace components during heat-up that produces lower flue gas temperatures (i.e, lower flue gas heat loss), and for systems incorporating flue closure devices, nearly all of this stored heat is credited as useful heat with no consideration of its probable loss through the cabinet walls as evidenced in the near-zero values of off-time sensible heat loss.

The furnaces were then tested with the draft control valve deactivated in the open position. Only relatively minor differences were noted in the flue temperature profiles; however, notable increases in the NBS calculated off-time heat losses resulted. This lowered the season average performances to nearly 2% below their steady-state values, but still significantly above the Rockwell/EPA measured efficiency with draft control in place.

SECTION 6

SUPPLEMENTARY LABORATORY TESTS

TEST OBJECTIVES

A supplementary laboratory testing effort was added to the program to answer several unanswered questions that had arisen during the execution of the program. These were: (1) A completely different approach for rating furnaces was formulated by the National Bureau of Standards, for which some reference data on the integrated furnace was needed; (2) no measured output efficiency data had been obtained in totally controlled laboratory conditions on any of the integrated systems; (3) the effect of two seasons of service on emissions characteristics was not known; and (4) the amenability of the integrated furnace design to conversion to natural gas was not fully defined.

The laboratory effort included testing of two of the furnaces from the field test according to the NBS-specific furnace seasonal performance rating procedure (Reference 11) in the "as is" condition and a cleaned, "like new" condition with supplementary tests conducted concurrently to obtain comparable measured output efficiency data and pollutant emissions data. The results of these tests then provided comparisons between the two efficiency rating methods and with data acquired in the field. The cleaned furnace remaining in the test installation was then to be fired with a commercially available gas conversion burner with sections of pyroflex insulation installed in the firebox to reduce the amount of heat extracted from the combustion zone in an effort to minimize NO_x and carbonaceous pollutants.

EFFICIENCY PERFORMANCE COMPARISON

NBS Seasonal Performance

The U.S. National Bureau of Standards is presently attempting to establish a standardized procedure for estimating the efficiency performance of residential furnaces (and boilers) operated in the cyclical mode. Indications are that the procedure is intended for industry-wide application as a rating standard for consumer information.

The NBS procedure (Reference 11) is basically an extension of the steady-state flue gas loss method of estimating efficiency performance based on measurements of flue gas temperature and composition. The procedure is based on the measurement of flue gas heat loss at four specified times during a firing cycle that starts from an above-ambient, pseudo-equilibrium condition to steady-state firing condition, and back through the cool-down phase. Flue gas temperatures are taken at 0.5 and 2.5 minutes after burner-start, then 1.5 and 9.0 minutes after burner-off. These temperatures are then used to estimate dynamic thermal losses based on a hypothetical 3.87-min-on/13.30-min-off firing cycle, which the NBS investigators apparently believe to be representative of the entire heating season for warm-air furnaces fired with any of the common fuels, to adjust the steady-state performance to an estimate of average performance over the entire heating season.

Some of the assumptions included in the formulation of the procedure are simplified, which leads to some difficulties for use in scientific applications. The procedure involves measurements only in the flue gas (i.e, estimates only the flue gas heat loss) and does not consider any other losses. This leads to the definition of efficiency performance based on the assumption that any heat not lost out the flue is considered to be useful heat and thus credited to the furnace efficiency performance. The output efficiency measurement method developed for the field test differs in that only the heat delivered to the bonnet (inlet to the dwelling distribution system) is accounted as useful heat. This leads to significant differences in the results, as will be shown later.

Since measured efficiency data of other furnaces operated in a cyclic mode are not readily available for comparison with the integrated furnace field test data, a supplementary effort was initiated to acquire additional data from the integrated furnaces using the NBS procedure.

The two furnaces (Units 1 and 2) were installed in the laboratory to conduct the NBS procedure first in the "used" condition, then in a cleaned, "like new" condition, both using a specified 1.52-m (5-ft) stack. Figure 28 is a photograph of the laboratory facility showing one of the furnaces installed in the test position. The laboratory results are presented in Table 16, showing some differences from the field-acquired data, but closer agreement of NBS estimated seasonal performance ratings between the two units (88.4% for Pond and 88.1% for Gravon). The estimates of seasonal performance still remain well above the respective steady-state performance values.

The combustor/heat exchanger assemblies were removed and the heat transfer surfaces cleaned by sandblasting. Approximately 1.7 and 1.2 kg of contaminants, primarily iron oxide, were removed from the Pond and Gravon heat exchangers, respectively. The results in Table 16 show notable increases in steady-state efficiency performances with corresponding increases in estimated seasonal performances. Both furnaces were estimated to perform over a heating season at an unrealistically high level of 89% efficiency, while the measured efficiencies using the Rockwell/EPA method show a performance at 22.5% utilization of about 70%.

The differences between the two measurement procedures, as stated earlier, stem primarily from differences in the definitions of "useful heat." The results show no reliable correlation between the two methods, and quantitative

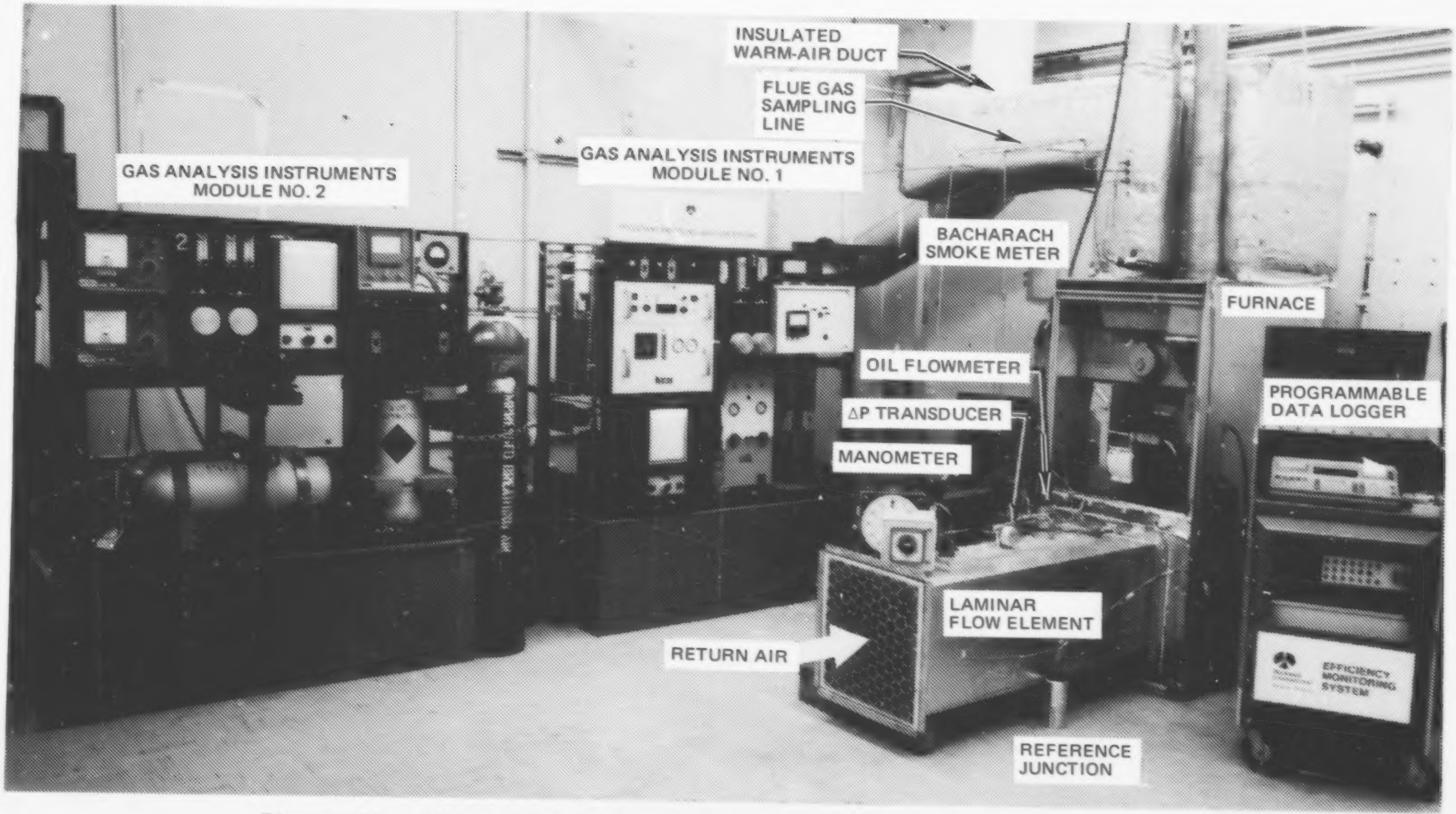
INSULATED WARM-AIR DUCT
FLUE GAS SAMPLING LINE
GAS ANALYSIS INSTRUMENTS MODULE NO. 2
GAS ANALYSIS INSTRUMENTS MODULE NO. 1
BACHARACH SMOKE METER
FURNACE
OIL FLOWMETER
PROGRAMMABLE DATA LOGGER
ΔP TRANSDUCER
MANOMETER
LAMINAR FLOW ELEMENT
RETURN AIR
REFERENCE JUNCTION
EFFICIENCY MONITORING SYSTEM

Figure 28. Photograph of the Residential Furnace Pollutant Emissions and Efficiency Measurement Laboratory System

TABLE 16

COMPARISON OF THE RESULTS OF THE NBS FURNACE RATING PROCEDURE FOR THE POND AND GRAVON FURNACES IN THE FIELD AND IN THE LABORATORY

System / Efficiency Performance	Pond (Unit 1)			Gravon (Unit 2)		
	Field Test %	Laboratory Test %	(Cleaned HX) Laboratory %	Field Test %	Laboratory Test %	(Cleaned HX) Laboratory %
Steady-State Operation						
Latent Heat Loss	-6.50	-6.50	-6.50	-6.50	-6.50	-6.50
Sensible Heat Loss (Flue)	-9.90	-9.30	-6.80	-9.20	-9.00	-7.60
η_{SS}	83.60	84.20	86.70	84.30	84.50	85.90
Cyclical Operation						
Latent Heat Loss	-6.50	-6.50	-6.50	-6.50	-6.50	-6.50
Sensible Heat Loss (Flue)						
On	-7.50	-4.96	-4.17	-6.27	-5.29	-4.38
Off	-0.10	-0.12	-0.09	-0.10	-0.12	-0.10
$\bar{\eta}_{NBS}$ Seasonal	85.90	88.42	89.24	87.12	88.09	89.02
$\bar{\eta}_{Rockwell/EPA^*}$	67.5	65.5	70.0	75.2	73.0	70.0
$\bar{\eta}_{Rockwell/EPA^{**}}$ Seasonal	70.2			75.6		

*Measured Output Efficiency, Test Data at t_R = 22.5%.

**Estimated Seasonal Efficiency based on field timing data and Correlation No. 4.

comparisons between data resulting from the two measurement procedures are not recommended.

Measured Output Efficiency Results

The effect of a laboratory installation upon output efficiency characteristics was also of interest, so output efficiency measurements were taken while the furnaces were installed on the test pad.

The field test results showed subtle differences in the dropoff in performance with decreasing utilization which were speculated to be due to individual site characteristics, especially differences in flue height. Thus, tests of two of the furnaces under identical installations were expected to produce nearly identical results. Figure 29 shows the laboratory test results of both furnaces overlayed on their respective field test data plots. The laboratory data, obtained with a 1.52-m (5-ft) flue pipe, show surprisingly little difference from the corresponding field test data taken with 6- to 9-m (20- to 30-ft) flue heights at the field installations. The combination of the draft control flap on the furnace and the barometric control valve on the flue pipe functioned more effectively than had been estimated in decoupling the furnace from the aspiration potential of the flue. The data, in both cases, appear unchanged throughout the span of the data, down to very low-utilization levels of 15 to 20% where the effect of the flue height was expected to be most pronounced. The performance of the integrated furnace system appears to be relatively independent of the sites' influences, and the differences in performance characteristics between the six test furnaces must be caused by differences within each furnace system.

The field test efficiency performance data showed varying degrees of "scatter," the causes of which were not identified during the field test. It was surmised that the conditions in the flue (e.g., wind, cooldown, etc.) varied more at some sites than at others, thus affecting standby heat losses. It was also surmised that inconsistent operation of the furnace control system (e.g., spring-wound thermostats) may be the cause of the data scatter. Close observation and control of the operation of the furnace in the laboratory revealed that the inconsistent operation of a furnace control device, specifically the spring-wound, bi-metallic fan thermostat switch, was a major cause of the data scatter. This is evident in the data plots in Figure 29 where the firing of the furnace was "locked" onto various utilization levels with a repeat cycle timer and fired through six or eight identical firing cycles. The results appear as vertical "stacks" of data points, fixed at given utilization levels and varying in heat output efficiency caused by varying levels of heat retained in the furnace with inconsistent "blowdowns" by the fan thermostat.

After cleaning of the firebox/heat exchanger assemblies to a "like new" condition, the furnaces were retested, and the measured output efficiency results are presented in Figure 30. Both furnaces generally show improved performance; however, the Gravon unit's characteristics at low utilization levels show a steeper dropoff in performance than its prior profile. The

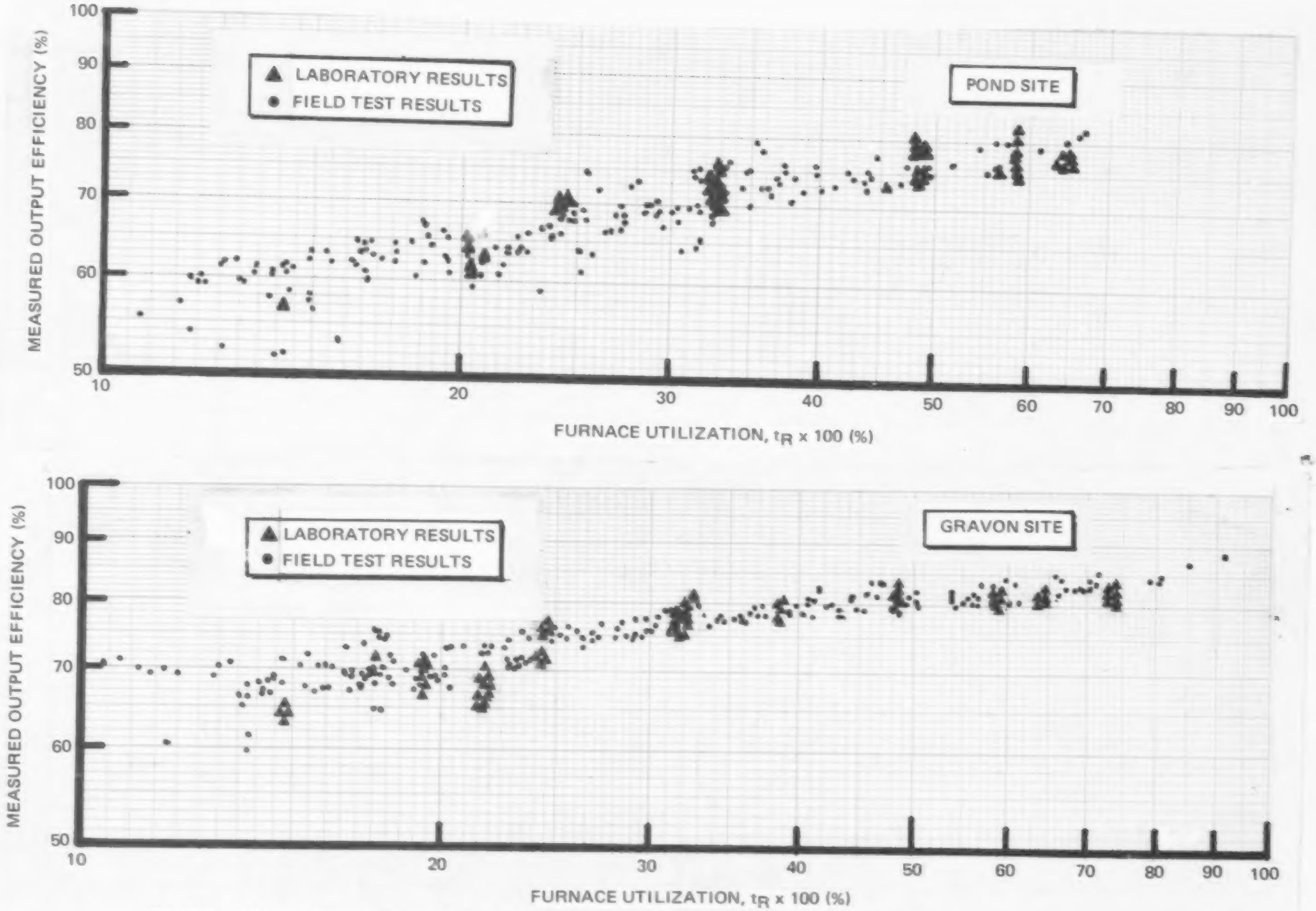

Figure 29. Comparison of Laboratory Test Results with Field Test Results for the Pond and Gravon Site Integrated Furnace Units

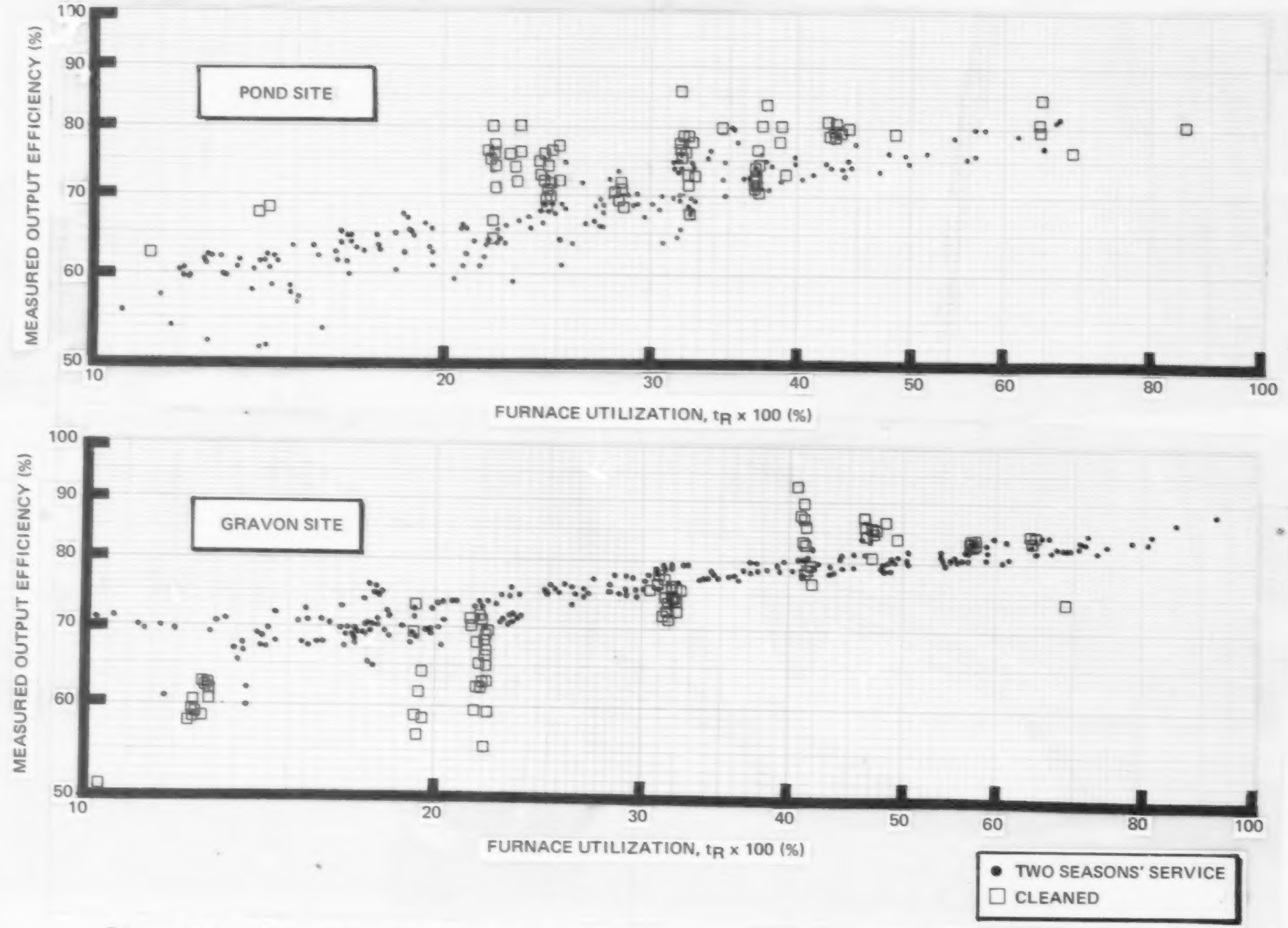

Figure 30. Comparison of Efficiency Performance Before and After Cleaning of the Heat Exchanger Surfaces in the Pond and Gravon Integrated Furnace Units

spread in the data also increased somewhat in both cases, spanning up to 17 percentage points in some instances. The most obvious change in the furnaces is, of course, the combustion gas-side heat transfer characteristics; however, changes in its heat storage characteristics may also have occurred. Unfortunately, comparison with the NBS results are made at the 22.5% utilization level, and this results in an unusually low measured efficiency performance after cleaning (see Table 16).

Although the changes in the efficiency performance of the two furnaces appear divergent when compared to the previous performance characteristics, their "like new" conditions bring them closer to being mechanically identical than their previous used condition. The performance data from both furnaces in their "cleaned" condition were compared, and the comparison is presented in Figure 31. A very definite overlap in the two sets of data can be seen. Except for a few points at the lower end of the tests at 20% utilization (NBS method assumes 22.5%) and some at the high end at 41% utilization, the data sets appear nearly identical in general characteristics. Considering the slight difference in stoichiometric ratio conditions (1.25 vs 1.31), the wide span of the data scatter does allow a great flexibility in interpretation. The scatter also reduces the effectiveness of statistical analyses. Least-squares correlations for the respective data sets, shown in Figure 31, show a difference in the slopes of the resultant characteristic curves. A correlation based on the combined data set, however, produces a characteristic curve that reaches 83.0% efficiency at steady state ($t_R = 1.0$) but drops off at a rate approximately twice that which was nominally the average rate found in the field. The relatively small number of data points, along with the large degree of scatter, prevents the formulation of a "universal" performance curve for the integrated furnace units.

POLLUTANT EMISSIONS

To obtain meaningful efficiency performance comparisons, the operating conditions needed to be close to the levels maintained in the field. In meeting this criterion, the full complement of flue gas analyzers was used to obtain supplementary pollutant emissions data for evaluation of long-term emissions reduction performance of the integrated furnace system.

The results of the laboratory tests are presented in Table 17, along with the respective measurements obtained at the last field visit at the field sites. The NO emissions are notably lower in the laboratory tests because the laboratory stock of fuel oil contained lower nitrogen concentrations than the oil delivered to the sites during the later months of the field test. The results with the original laboratory oil stock show the familiar levels of NO $\leq$ 0.65 g/kg, upon which field test goals were based. The CO and UHC concentrations for both furnaces remain well under the test goals of 1.00 and 0.10 g/kg, respectively. The only notable difference between the prefield test laboratory results is the smoke emissions measured on the furnaces following the two heating seasons of service in the field test. The smoke emissions were thought to be caused by fouled nozzles from high sludge concentrations in some of the oil deliveries; however, the same nozzles (one heating season of

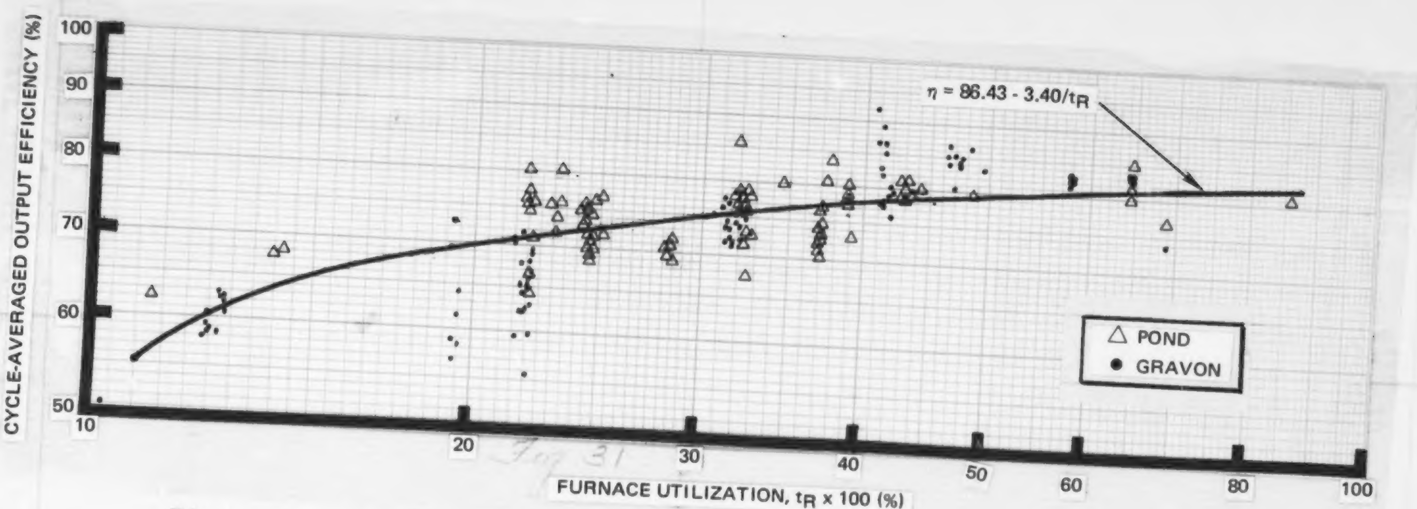

Figure 31. Comparison of Measured Output Efficiency Laboratory Results Between the Pond and Gravon Furnaces in Cleaned Condition

TABLE 17

CYCLE-AVERAGED POLLUTANT EMISSIONS CONCENTRATIONS FROM THE POND AND GRAVON INTEGRATED FURNACES TESTED IN THE LABORATORY

			RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE
POND	2 Seasons		1	1.25	12.5	4.5	30	31	4	.50	.549	.036	1.1
			2	1.24	12.6	4.4	31	30	4	.53	.529	.036	1.1
		SS	3	1.23	12.6	4.3	20	36	2	.33	.631	.019	.8
	Clean HX		4	1.26	12.4	4.6	31	32	4	.53	.571	.038	.0
			5	1.25	12.5	4.6	31	32	4	.53	.570	.036	.0
		SS	6	1.25	12.6	4.5	20	37	2	.33	.655	.019	0
GRAVON	2 Seasons		11	1.32	12.0	5.5	40	33	4	.70	.618	.040	1.0
			12	1.32	12.0	5.6	40	32	4	.70	.602	.040	1.0
		SS	13	1.32	12.0	5.5	20	39	2	.35	.730	.020	1.0
	Clean HX		14	1.30	12.2	5.4	38	32	3	.66	.594	.035	0
			15	1.31	12.2	5.5	35	31	3	.61	.578	.035	0
		SS	16	1.31	12.2	5.5	20	38	2	.35	.709	.020	0

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service) produced no measurable smoke readings after the firebox/heat exchanger surfaces were cleaned to a "like new" condition. The higher sludge concentrations in the fuel oil may have accelerated the accumulation of soot in the heat exchanger. The furnaces were fired for a significant period of time in the course of acquiring all the efficiency performance data with periodic checks on flue gas emissions, so the likelihood of the smoke readings being caused by residual soot eroding off the walls and carried out is low; however, the particulate concentration required to produce a No. 1 Bacharach smoke reading is also low. The cause of the slightly higher smoke readings from the "used" furnaces may have been combinations of carbon and ferrous oxide (FeO) or ferrous sulfate ($FeSO_4$); however, these samples were not analyzed in this effort.

NATURAL GAS CONVERSION

The alternate fuels experiments conducted in Phase I of this program (Reference 12) with the integrated furnace system included tests with natural gas. The tests used a commercially available, powered, gas burner in place of the optimized oil burner. The gas burner, a Mid-Continent (Midco) DS5850 burner, incorporated state-of-the-art features such as direct spark ignition and solid-state electronics. The previous experiments indicated that the finned firebox extracted too much heat and was quenching the reaction, thus producing low NO concentrations. So additional testing was implemented to investigate if simple modification of the heat transfer characteristics of the finned firebox could improve the CO and UHC emissions to an acceptable level.

Pollutant Emissions

T18

The furnace used was the cleaned Gravon unit, first fired as before into the unmodified finned firebox at an equivalent firing rate of 31,630 W (108,000 Btu/h). Table 18 shows the results of both cyclical and steady-state firings. The previous tests were conducted in the welded, finned prototype firebox; however, the results in Table 18 show similar characteristics with slight improvements in the CO and UHC emissions. The nominal NO level shows an increase, apparently all caused by slightly lower cooling from the shorter finned cast-iron firebox. The results show acceptable CO and UHC emission concentrations at a relatively high stoichiometric ratio of 1.49.

T19

A 0.305-m (12-in.) diam disc of pyroflex insulation, covering approximately 20% of the inside surface of the firebox, was placed on the bottom of the combustor to inhibit heat extraction from the combustion zone, and the results are tabulated in Table 19. Acceptable CO and UHC concentrations were obtained at a reasonably efficient operating condition of SR 1.28; however, the NO emissions increased to approximately 1.0 g/kg, significantly higher than that of the optimized oil burner.

T20

A smaller disc of 0.216-m (8.5-in.) diam, half the surface area of the first disc, was then installed in the firebox. Table 20 shows that the resultant compromise provided favorable tradeoffs, with acceptable levels of CO and UHC emissions at SR $\approx$1.28, with an approximately 30% reduction in NO emissions

TABLE 18

POLLUTANT EMISSION CONCENTRATIONS FROM THE INTEGRATED FURNACE BY A NATURAL GAS CONVERSION BURNER

	RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO G/KG*	NO G/KG*	UHC G/KG*	BACH. SMOKE	NET TFG C
4 Minutes-On/8 Minutes-Off	1	1.62	6.9	8.3	130	46	16	2.50	.948	.176	0	
	2	1.54	7.3	7.6	95	48	10	1.73	.937	.104	0	197
	3	1.48	7.7	7.1	82	46	10	1.43	.861	.105	0	196
	4	1.44	8.0	6.8	97	42	11	1.66	.763	.107	0	197
	5	1.33	8.6	5.6	1467	22	100	22.89	.368	.891	0	196
	6	1.44	7.9	6.8	100	38	18	1.70	.693	.175	0	196
	7	1.53	7.5	7.6	60	41	14	1.08	.793	.144	0	196
	8	1.64	6.9	8.5	70	37	13	1.36	.771	.144	0	197
	9	1.70	6.7	9.1	100	38	16	2.02	.824	.165	0	204
	10	1.84	6.1	9.9	157	30	22	3.46	.704	.275	0	215
	11	1.43	8.0	6.7	85	36	8	1.43	.651	.077	0	
	12	1.38	7.6	5.8	107	42	8	1.76	.732	.072	0	145
	13	1.49	7.5	7.0	45	40	9	.79	.752	.090	0	
	14	1.66	6.8	8.6	140	35	14	2.77	.736	.157	0	
	15	1.74	6.5	9.3	187	36	22	3.89	.798	.266	0	154
	16	1.32	7.8	5.0	≥1599	10	3000	≥24.77	.166	26.535	1.0	
Steady-State	17	1.29	9.0	5.1	953	37	350	14.41	.599	3.024	0	
	18	1.45	7.8	6.6	40	54	3	.68	.989	.029	0	
	19	1.39	8.3	6.2	66	53	3	1.09	.926	.028	0	
	20	1.54	7.4	7.7	40	56	2	.73	1.094	.021	0	
	21	1.64	6.9	8.5	70	56	4	1.36	1.160	.044	0	
	22	1.69	6.7	8.9	85	50	6	1.70	1.074	.069	0	
	23	1.50	7.7	7.4	40	57	2	.71	1.083	.020	0	
	24	1.34	6.6	5.6	254	49	40	3.99	.824	.359	0	

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TABLE 19

POLLUTANT EMISSION CONCENTRATIONS FROM THE NATURAL GAS-FIRED INTEGRATED FURNACE WITH A 0.30-m DIAM INSULATOR INSTALLED IN THE FIREBOX

KG* = HEAT EQUIV. OF 1 KG OF NO.2 FUEL OIL

	RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO G/KG*	NO G/KG*	UHC G/KG*	BACH. SMOKE	NET TFG C
4 Min-On/8 Min-Off	25	1.34	8.5	5.6	20	63	5	.32	1.064	.045	0	144
	26	1.28	8.8	4.7	35	70	5	.52	1.123	.043	0	
	27	1.45	7.7	6.6	87	54	11	1.50	.987	.107	0	
	28	1.52	7.4	7.4	90	45	20	1.62	.866	.205	0	
	29	1.65	6.9	8.6	209	37	23	4.08	.773	.256	0	
	30	1.29	9.0	5.0	25	55	5	.36	.891	.043	0	
Steady-State	31	1.29	9.0	5.0	20	59	1	.30	.956	.009	0	
	32	1.45	7.9	6.8	25	56	1	.43	1.058	.010	0	
	33	1.51	7.6	7.4	30	54	2	.53	1.030	.020	0	
	34	1.67	6.7	8.7	120	37	10	2.38	.787	.113	0	209
	35	1.79	6.2	9.5	231	29	20	4.93	.662	.243	0	213
	36	1.39	8.2	6.1	15	61	1	.24	1.065	.009	0	
	37	1.23	8.4	3.8	≥1599	16	3000	≥22.94	.246	24.575	3.0	
	38	1.20	9.9	3.8	397	60	90	5.57	.900	.720	0	
	39	1.28	9.1	4.9	20	69	10	.30	1.107	.086	0	
	40	1.22	9.5	4.0	143	63	25	2.05	.961	.203	0	
4-On/8-Off	41	1.20	9.7	3.8	198	54	25	2.79	.813	.201	0	
	42	1.23	9.3	4.2	87	54	6	1.27	.835	.049	0	
	43	1.23	9.3	4.1	75	60	8	1.08	.923	.066	0	

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TABLE 20

POLLUTANT EMISSION CONCENTRATIONS FROM THE NATURAL GAS-FIRED INTEGRATED FURNACE WITH A 0.22-m DIAM INSULATOR INSTALLED IN THE FIREBOX

(Sheet 1 of 2)

KG* = HEAT EQUIV. OF 1 KG OF NO.2 FUEL OIL

--------- STEADY-STATE ---------

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO G/KG*	NO G/KG*	UHC G/KG*	BACH. SMOKE	NET TFG C
44	1.68	6.5	8.5	220	36	35	4.37	.767	.398	0	180
45	1.62	6.7	8.0	157	43	13	3.03	.883	.142	0	198
46	1.52	7.3	7.3	90	51	1	1.62	.981	.010	0	198
47	1.42	7.8	6.4	45	62	1	.75	1.113	.010	0	197
48	1.37	8.2	5.8	35	67	1	.56	1.153	.009	0	197
49	1.28	8.8	4.8	40	68	2	.60	1.096	.017	0	197
50	1.23	9.1	4.1	130	64	8	1.87	.989	.066	0	197
51	1.16	9.3	3.0	≥1599	32	3000	≥21.67	.464	23.219	2.0	189
52	1.18	9.7	3.4	1163	54	180	16.00	.796	1.414	0	192
53	1.30	8.6	5.0	20	65	2	.31	1.064	.017	0	197

TABLE 20

POLLUTANT EMISSION CONCENTRATIONS FROM THE NATURAL GAS-FIRED INTEGRATED FURNACE WITH A 0.22-m DIAM INSULATOR INSTALLED IN THE FIREBOX

(Sheet 2 of 2)

KG* = HEAT EQUIV. OF 1 KG OF NO.2 FUEL OIL

4 Minutes-On/8 Minutes-Off

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO G/KG*	NO G/KG*	UHC G/KG*	BACH. SMOKE	NET TFG C
54	1.41	8.1	6.4	53	45	8	.88	.799	.076	0	
55	1.28	9.2	5.0	55	46	7	.83	.740	.060	0	
56	1.22	9.7	4.1	105	44	6	1.50	.672	.049	0	
57	1.25	7.3	3.5	105	46	7	1.54	.721	.058	0	
58	1.07	10.1	1.5	≥1599	35	120	≥20.02	.469	.858	0	
59	1.22	7.5	3.2	242	43	32	3.47	.658	.261	0	
60	1.27	8.5	4.5	45	44	9	.67	.704	.077	0	
61	1.36	8.0	5.6	39	46	11	.62	.790	.101	0	
62	1.55	7.1	7.5	157	36	25	2.89	.706	.261	0	
63	1.68	6.4	8.4	290	30	45	5.78	.639	.511	0	
64	1.30	8.7	5.0	30	64	2	.46	1.044	.017	0	
65	1.43	7.8	6.5	85	40	9	1.43	.722	.087	0	179
66	1.51	7.3	7.1	95	39	7	1.69	.743	.071	0	189
67	1.56	7.0	7.6	115	38	10	2.13	.753	.106	0	198
68	1.70	6.5	8.8	167	34	35	3.38	.735	.404	0	
69	1.64	6.9	8.5	220	33	35	4.27	.686	.388	0	

in 4-min on/8-min off cyclical operation. The NO emission concentrations are slightly higher than those produced by the optimized oil burner; however, the burner was not modified to optimize firebox/burner matching or to minimize pollutants.

Efficiency Performance

The "optimized" natural gas-firing integrated furnace configuration was then fired at its "best" stoichiometric ratio condition of 1.28 and at a less efficient condition of SR = 1.64 to obtain information on its NBS estimated seasonal performance ratings and its output efficiency performance characteristics.

NBS Performance Rating Results — The results of the NBS furnace rating procedure are presented in Table 21, along with comparative oil-fired test data. The data show nearly a seven-percentage-point lower steady-state efficiency performance with the natural gas-fired configuration, primarily caused by the inherently higher water vapor content (i.e., higher heat capacity) of the product flue gas. This difference increases to nearly nine percentage points in the estimated seasonal performance; however, the difference is more on the order of four percentage points due to credit given to the oil-fired configuration for its draft closure device, which was not on the gas-fired furnace system.

Both steady-state and the estimated seasonal performance level decreased with the increase in excess air throughput to 77.05 and 75.22%, respectively, at SR = 1.64.

Output Efficiency Results — The natural gas-converted integrated furnace was fired over a range of utilization at the two selected stoichiometric ratio conditions to obtain measurements of the thermal efficiency characteristics of this configuration.

The results are presented graphically in Figure 32, showing the performance with natural gas fired at SR = 1.28 and 1.64, along with the oil-fired integrated furnace data taken immediately prior to the conversion to natural gas fuel. The oil-fired efficiency performance is generally slightly higher than the natural gas-fired results by about six or seven percentage points at the higher utilization levels. This is caused primarily by the higher flue gas latent-heat losses (higher water vapor content in the product gas) and secondarily by inhibited heat transfer resulting from the partially insulated firebox and lower reaction temperatures.

The data from S.R. = 1.28 generally appear to be approaching the steady-state efficiency value of 80.8% and dropping off at a rate about equal to that of the oil-fired configuration. Although the optimized oil burner is equipped with a standby draft closure device, the 1.52-m (5-ft) laboratory stack produces only a minimal aspiration potential at this low-excess air (28%) setting. This may not be typical for all gas burners, however, since the gas burner

TABLE 21

COMPARISON OF THE RESULTS OF THE NBS FURNACE RATING PROCEDURE FOR THE GRAVON FURNACE FIRE WITH NO. 2 FUEL OIL AND WITH NATURAL GAS

Efficiency Performance / System	Oil-Fired	Natural Gas-Fired	
	S.R. = 1.32 %	S.R. = 1.28 %	S.R. = 1.64 %
Steady-State Operation			
Latent Heat Loss	-6.50	-9.55	-9.55
Sensible Heat Loss	-6.80	-9.65	-13.40
$\overline{\eta}_{SS}$	86.70	80.80	77.05
Cyclical Operation			
Latent Heat Loss	-6.50	-9.55	-9.55
Sensible Heat Loss ON	-4.17	-5.04	-8.43
Sensible Heat Loss OFF	-0.09	-4.84	-6.80
$\overline{\eta}_{NBS\ Season}$	89.24	80.57	75.22
$\overline{\eta}_{Rockwell/EPA}$*	70.0	67.0	65.0

*Measured Output Efficiency, Test Data at t_R = 22.5%.

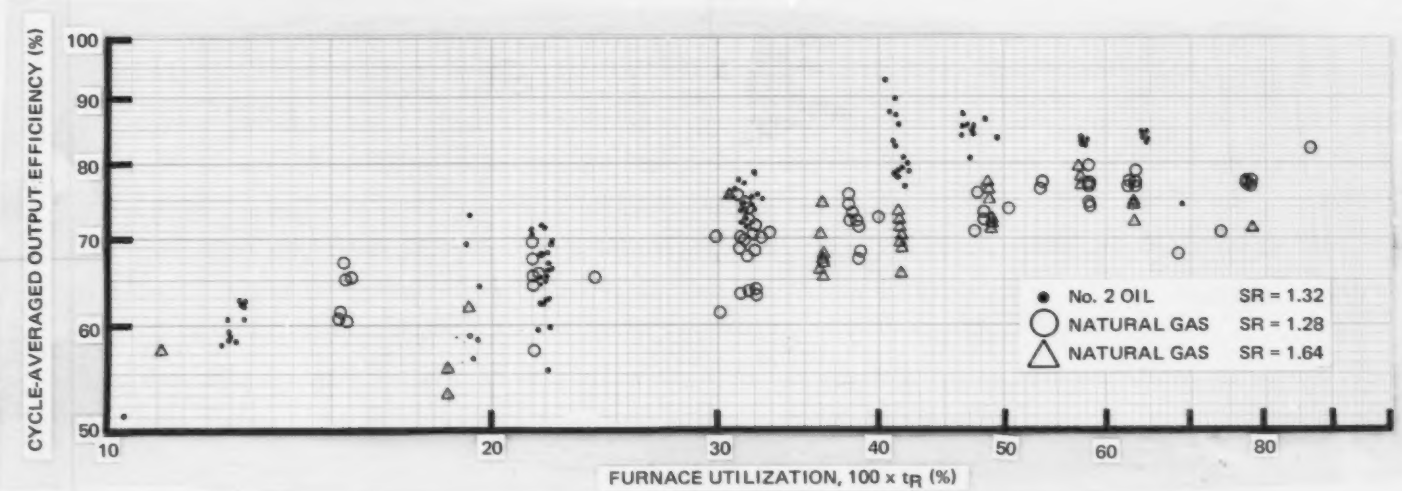

Figure 32. Comparison of Efficiency Performance of Oil-Fired and Natural Gas-Fired Integrated Furnace Configurations

used is an atypical, powered-fan-type burner with a small, variable, combustion-air inlet passage that inhibits flow through the furnace during standby.

The results from the tests at S.R. = 1.64 appear to be slightly lower than the S.R. = 1.28 tests, as indicated by the steady-state flue gas loss calculation. Least-squares statistical analysis, however, cannot verify this observation with the existing data scatter, and the resultant curve fits are nearly identical above 30% utilization. The curve fits do show a greater dropoff in performance at lower utilization levels for the higher excess air case (64%), which is likely, since a larger opening would be available for naturally aspirated flow.

Natural Gas-Converted Integrated Furnace

The results of the natural gas-fired pollutant emissions experiments demonstrated that only a very minor modification is required to achieve acceptable pollutant emissions at efficient operating conditions in converting the oil-fired integrated furnace system to natural gas fuel. The experiments indicated that the benefits of the cooled firebox can be utilized by natural gas burners, as the results showed NO concentrations approximately 20 to 30% lower than the levels shown in the data discussed in Reference 12. Simultaneously, very high thermal efficiency performance would be obtained from this conversion configuration. Additional work is needed to optimize the gas burner and integrate it with the firebox in an optimum fashion.

REFERENCES

1. Combs, L. P., and A. S. Okuda, "Design Optimization and Field Verification of an Integrated Residential Furnace," in EPA-600/7-77-073a, Proceedings of Second Stationary Source Combustion Symposium, New Orleans, Louisiana, pp. 85-121, 1977

2. Dickerson, R. A., and A. S. Okuda, Design of an Optimum Distillate Oil Burner for Control of Pollutant Emissions, in EPA-650/2-74-047, Final Report on Contract 68-02-0017, Rockwell International, Rocketdyne Division, Canoga Park, California, p. 251, 1974

3. Combs, L. P., and A. S. Okuda, Residential Oil Furnace System Optimization, Phase I, in EPA-600/2-76-038, Phase Report on Contract 68-02-1819, Rocketdyne Division, Canoga Park, California, p. 210, 1976

4. Combs, L. P., and A. S. Okuda, Residential Oil Furnace System Optimization, Phase II, in EPA-600/2-77-028, Phase Report on Contract 68-02-1819, Rocketdyne Division, Canoga Park, California, p. 122, 1977

5. Combs, L. P., and A. S. Okuda, "Design Criteria for Reducing Pollutant Emissions and Fuel Consumption by Residential Oil-Fueled Combustors," Paper 76-WA/Fu-10, presented at the 97th ASME Winter Annual Meeting, New York, New York, 1976

6. Barrett, R. E., S. E. Miller, and D. W. Locklin, Field Investigation of Emissions from Combustion Equipment for Space Heating, in EPA-R2-73-084a (also API Publication 4180), Environmental Protection Agency, Research Triangle Park, North Carolina, p. 206, 1973

7. American National Standard Performance Requirements for Oil-Powered Central Furnaces, ANSI Z91.1, 1972; American National Standards Institute, Inc., New York, New York, p. 24, 1972

8. Janssen, J. E., and U. Bonne, Improvement of Seasonal Efficiency of Residential Heating Systems, Paper 76-WA/Fu-7, presented at the 97th ASME Winter Annual Meeting, New York, New York, p. 5, 1976

9. Peoples, G., "Sealed Oil Furnace Combustion System Reduces Fuel Consumption," Addendum to the Proceedings, Conference on Improving Efficiency in HVAC Equipment and Components for Residential and Small Commercial Buildings, Purdue University, Lafayette, Indiana, pp. A66-A72, October 1974

10. Turner, D. W., et al., "Efficiency Factors for Domestic Oil Heating Units," in Addendum to the Proceedings, Conference on Improving Efficiency in HVAC Equipment and Components for Residential and Small Commercial Buildings, Purdue University, Lafayette, Indiana, pp. A18-A22, October 1974

11. Recommended Testing and Calculation Procedures for Determining the Seasonal Performance of Residential Central Furnaces and Boilers, NBSIR78-1543, Department of Energy, Washington, D.C., October 1978

12. Okuda, A. S., and L. P. Combs, Design Optimization and Field Verification of an Integrated Residential Furnace, Phase I, EPA-600/7-79-037a, Phase Report on Contract 68-02-2174, Rockwell International, Rocketdyne Division, Canoga Park, California, p. 148, 1979

APPENDIX A

FIELD TEST DATA ACQUISITION AND REDUCTION COMPUTER CODES

TABLE A-1

LISTING OF THE POWER INTERUPTION RECOVERY CONTROL CODE FOR THE H/P SYSTEM 3051A DATA LOGGER

(Sheet 1 of 2)

```
FILE      0
TYPE      0
USED      185
MAX       250


0000 NOP
0001 NOP
0002 NOP
0003 NOP
0004 NOP
0005 1
0006 STO      A
0007 4
0008 STO      F
0009 FOR      A→F
0010 PRNTα
0012 LINE
0013 LINE
0014 *
0015
0016 *
0017
0018 *
0019
0020 *
0021
0022 *
0023
0024 *
0025
0026 *
0027
0028 *
0029 ENDα
0030 NEXT     A
0031 PRNTα
0033 LINE
0034 LINE
0035 P
0036 O
0037 W
0038 E
0039 R
0040
0041 F
0042 A
0043 I
0044 L
0045 U
0046 R
0047 E
0048 ENDα
0049 1
0050 STO      A
0051 FOR      A→F
0052 PRNTα
0054 LINE
0055 LINE
0056 *
0057 .
0058 *
0059
0060 *
0061
0062 *
0063
0064 *
0065
0066 *
0067
0068 *
0069
0070 *
0071 ENDα
0072 NEXT     A
0073 PRNTα
0075 LINE
0076 LINE
0077 E
0078 X
0079 A
0080 M
0081 I
0082 N
0083 E
0084
0085 D
0086 A
0087 T
0088 A
0089
0090 LINE
0091 C
0092 A
0093 R
0094 E
0095 F
0096 U
0097 L
0098 L
0099 Y
0100 LINE
0101 LINE
0102 ENDα
0103 CLEAR
0104 STO      A
0105 2
0106 RCL      A
0107 +
0108 STO      A
0109 IDENT
0110 ROLL↓
0111 IF 0
0112 GOTO     0123
0114 ROLL↓
0115 IF 0
0116 GOTO     0178
0118 1
0119 0
0120 8
0121 RCL      A
0122 IF X=Y
0123 GOTO     0128
```

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TABLE A-1

LISTING OF THE POWER INTERUPTION RECOVERY CONTROL CODE FOR THE H/P SYSTEM 3051A DATA LOGGER

(Sheet 2 of 2)

```
0125 1
0126 GOTO   0106         0177 SFG     4
0128 CLEAR               0178 RCL     A
0129 1                   0179 STO     R000
0130 +⇌-                 0181 CLEAR
0131 STO     A           0182 1
0132 IDENT               0183 LD&GO
0133 ROLL↓               0184 END
0134 IF 0
0135 GOTO   0151
0137 ROLL↓
0138 IF 0
0139 GOTO   0173
0141 1
0142 0
0143 8
0144 +⇌-
0145 IF X=Y
0146 GOTO   0153
0148 RCL     A
0149 1
0150 -
0151 GOTO   0131
0153 PRNTα
0155 LINE
0156 LINE
0157 D
0158 A
0159 T
0160 A
0161
0162 T
0163 A
0164 P
0165 E
0166
0167 F
0168 I
0169 L
0170 L
0171 E
0172 D
0173 LINE
0174 LINE
0175 LINE
0176 ENDα
```

```
AUTO START

* * * * * * * *

* * * * * * * *

* * * * * * * *

* * * * * * * *

POWER FAILURE

* * * * * * * *

* * * * * * * *

* * * * * * * *

* * * * * * * *

EXAMINE DATA
CAREFULLY
```

TABLE A-2

LISTING OF THE FURNACE THERMAL EFFICIENCY MONITORING CONTROL CODE FOR THE H/P SYSTEM 3051A DATA LOGGER

(Sheet 1 of 5)

```
FILE     1
TYPE     0
USED     663
MAX      900


0000 NOP
0001 NOP
0002 NOP
0003 NOP
0004 CLRA→J
0005 RCL     R000
0007 IF 0
0008 2
0009 STO     R000
0011 1
0012 #REGS
0013 5
0014 0
0015 #REGS
0016 9
0017 STO     R001
0019 4
0020 .
0021 5
0022 6
0023 1
0024 7
0025 STO     R004
0027 2
0028 .
0029 7
0030 9
0031 4
0032 1
0033 STO     R006
0035 CFG     1
0036 CFG     2
0037 2
0038 2
0039 ENTER↑
0040 CALL    5α
0042 ?
0043 @
0044 B
0045
0046 F
0047 2
0048 R
0049 7
0050 A
0051 1
0052 H
0053 1
0054 M
0055 3
0056 T
0057 3
0058 ENDα
0059 9
0060 ENTER↑
0061 CALL    5α
0063
0064 0
0065 1
0066 ENDα
0067 GOSUB   L01
0069 4
0070 IF X≥Y
0071 GOTO    0081
0073 IF CFG 1
0074 GOSUB   L02
0076 SFG     1
0077 1
0078 STO+    B
0079 GOTO    0091
0081 CFG     1
0082 1
0083 STO+    D
0084 .
0085 6
0086 3
0087 2
0088 6
0089 IF SFG 2
0090 STO+    D
0091 9
0092 ENTER↑
0093 CALL    5α
0095
0096 0
0097 2
0098 ENDα
0099 GOSUB   L01
0101 4
0102 IF X≥Y
0103 GOTO    0110
0105 1
0106 STO+    C
0107 SFG     2
0108 GOTO    0111
0110 CFG     2
0111 2
0112 2
0113 ENTER↑
0114 CALL    5α
0116
0117 F
0118 1
0119 ENDα
0120 9
0121 ENTER↑
0122 CALL    5α
0124
0125 0
0126 3
0127 ENDα
0128 GOSUB   L01
0130 IF CFG 2
0131 GOTO    0134
0133 STO+    F
0134 9
0135 ENTER↑
0136 CALL    5α
0138
0139 0
0140 4
0141 ENDα
0142 GOSUB   L01
0144 IF CFG 2
0145 GOTO    0150
0147 9
0148 ÷
0149 STO+    G
0150 9
0151 ENTER↑
```

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TABLE A-2

LISTING OF THE FURNACE THERMAL EFFICIENCY MONITORING CONTROL CODE FOR THE H/P SYSTEM 3051A DATA LOGGER

(Sheet 2 of 5)

```
0152 CALL    5α
0154
0155 0
0156 5
0157 ENDα
0158 GOSUB   L01
0160 RCL     H
0161 X⇌Y
0162 IF X≥Y
0163 STO     H
0164 9
0165 ENTER↑
0166 CALL    5α
0168
0169 0
0170 6
0171 ENDα
0172 GOSUB   L01
0174 IF CFG 2
0175 GOTO    0178
0177 STO+    I
0178 9
0179 ENTER↑
0180 CALL    5α
0182
0183 0
0184 8
0185 ENDα
0186 GOSUB   L01
0188 IF CFG 1
0189 GOTO    0192
0191 STO+    E
0192 2
0193 2
0194 ENTER↑
0195 CALL    5α
0197
0198 F
0199 4
0200 ENDα
0201 9
0202 ENTER↑
0203 CALL    5α
0205
0206 0
0207 7
0208 ENDα
0209 GOSUB   L01
0211 IF CFG 2
0212 GOTO    0037
```

```
0214 STO+    J
0215 GOTO    0037
0217 NOP
0218 NOP
0219 NOP
0220 NOP
0221 NOP
0222 LBL
---- 01
0224 .
0225 2
0226 2
0227 0
0228 9
0229 ENTER↑
0230 CALL    5α
0232 @
0233 H
0234 ENDα
0235 CLEAR
0236 2
0237 2
0238 CALL    5H
0240 RETURN
0241 NOP
0242 NOP
0243 NOP
0244 NOP
0245 LBL
---- 02
0247 CFG     3
0248 RCL     B
0249 IF 0
0250 GOTO    0253
0252 STO÷    E
0253 RCL     R004
0255 *
0256 5
0257 +
0258 0
0259 ROUND
0260 STO     B
0261 9
0262 9
0263 9
0264 9
0265 IF X<Y
0266 SFG
0267 ROLL↓
```

```
0268 6
0269 0
0270 ÷
0271 STO+    R002
0273 RCL     D
0274 RCL     R006
0276 *
0277 ENTER↑
0278 ENTER↑
0279 6
0280 0
0281 ÷
0282 STO+    R003
0284 ROLL↓
0285 1
0286 EEX
0287 5
0288 +⇌-
0289 *
0290 .
0291 9
0292 9
0293 9
0294 9
0295 IF X≥Y
0296 GOTO    0301
0298 SFG     3
0299 GOTO    0302
0301 ROLL↓
0302 STO+    B
0303 1
0304 STO+    R001
0306 RCL     B
0307 STO I   R001
0309 RCL     C
0310 IF 0
0311 GOTO    0423
0313 STO÷    F
0314 STO÷    G
0315 STO÷    I
0316 STO÷    J
0317 RCL     J
0318 LN
0319 2
0320 7
0321 .
0322 4
0323 9
0324 3
0325 8
0326 +⇌-
0327 *
```

TABLE A-2

LISTING OF THE FURNACE THERMAL EFFICIENCY MONITORING CONTROL CODE FOR THE H/P SYSTEM 3051A DATA LOGGER

(Sheet 3 of 5)

```
0328 1
0329 9
0330 1
0331 .
0332 5
0333 2
0334 1
0335 +
0336 STO     J
0337 RCL     F
0338 GOSUB   L03
0340 CALL    6M
0342 STO     F
0343 RCL     J
0344 RCL     G
0345 GOSUB   L03
0347 CALL    6M
0349 RCL     F
0350 -
0351 STO     G
0352 RCL     J
0353 RCL     E
0354 GOSUB   L03
0356 CALL    6M
0358 STO     E
0359 RCL     J
0360 RCL     H
0361 GOSUB   L03
0363 CALL    6M
0365 RCL     E
0366 -
0367 STO     H
0368 RCL     I
0369 .
0370 2
0371 7
0372 6
0373 9
0374 *
0375 STO     I
0376 ENTER↑
0377 *
0378 2
0379 5
0380 3
0381 1
0382 4
0383 .
0384 7
0385 +≑-
0386 *
0387 RCL     I
0388 1
0389 7
0390 6
0391 1
0392 7
0393 .
0394 2
0395 *
0396 +
0397 5
0398 8
0399 .
0400 2
0401 5
0402 1
0403 7
0404 +
0405 .
0406 0
0407 7
0408 6
0409 5
0410 *
0411 2
0412 8
0413 8
0414 ÷
0415 2
0416 7
0417 3
0418 RCL     F
0419 +
0420 ÷
0421 NOP
0422 NOP
0423 STO     I
0424 RCL     G
0425 *
0426 1
0427 .
0428 8
0429 *
0430 .
0431 2
0432 3
0433 6
0434 4
0435 *
0436 RCL     C
0437 *
0438 RCL     R004
0440 *
0441 6
0442 0
0443 ÷
0444 0
0445 ROUND
0446 STO     I
0447 RCL     H
0448 1
0449 0
0450 0
0451 0
0452 ÷
0453 STO+    I
0454 1
0455 STO+    R001
0457 RCL     I
0458 STO I   R001
0460 1
0461 STO+    R005
0463 FIX     0
0465 RCL     R005
0467 PRNTα
0469 LINE
0470 PRINT
0471
0472 F
0473 I
0474 R
0475 I
0476 N
0477 G
0478 S
0479 ENDα
0480 RCL     R002
0482 0
0483 ROUND
0484 PRNTα
0486 PRINT
0487
0488 M
0489 I
0490 N
0491 .
0492
0493 O
0494 N
0495 ENDα
```

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TABLE A-2

LISTING OF THE FURNACE THERMAL EFFICIENCY MONITORING CONTROL CODE FOR THE H/P SYSTEM 3051A DATA LOGGER

(Sheet 4 of 5)

```
0496 RCL     R003
0498 0
0499 ROUND
0500 PRNTα
0502 PRINT
0503
0504 M
0505 I
0506 N
0507 .
0508
0509 O
0510 F
0511 F
0512 ENDα
0513 4
0514 9
0515 RCL     R001
0517 IF X=Y
0518 SFG     3
0519 IF CFG 3
0520 GOTO    0626
0522 IF SFG 4
0523 GOTO    0615
0525 4
0526 0
0527 ENTER↑
0528 1
0529 0
0530 RCL     R000
0532 RCDATA
0533 PRNTα
0535 F
0536 I
0537 L
0538 E
0539
0540 PRINT
0541
0542 R
0543 C
0544 R
0545 D
0546 '
0547 D
0548 LINE
0549 ENDα
0550 1
0551 RCL     R000
0553 IF X<Y
0554 GOTO    0576
```

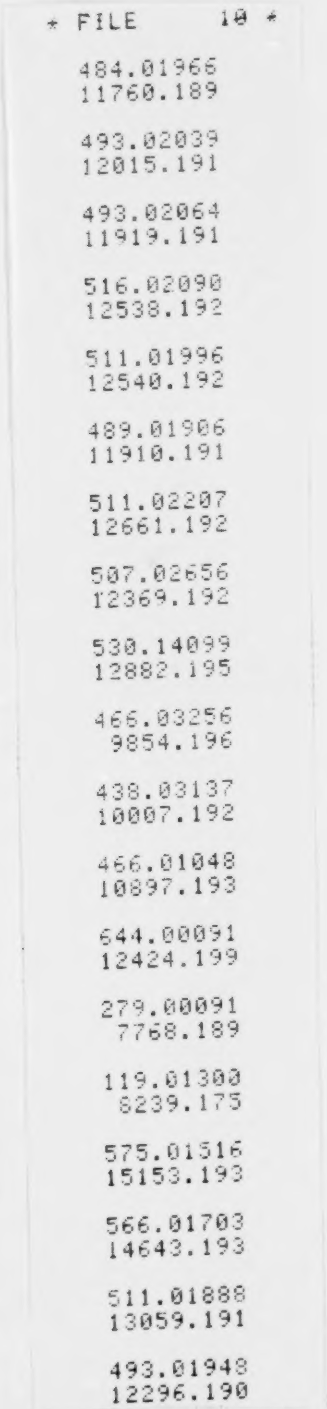
```
0556 1
0557 STO+    R000
0559 1
0560 0
0561 9
0562 RCL     R000
0564 IF X<Y
0565 GOTO    0615
0567 2
0568 2
0569 STO+    B
0570 1
0571 +⇌-
0572 STO     R000
0574 GOTO    0615
0576 1
0577 STO-    R000
0579 1
0580 0
0581 8
0582 +⇌-
0583 RCL     R000
0585 IF X≥Y
0586 GOTO    0615
0588 PRNTα
0590 LINE
0591 LINE
0592 D
0593 A
0594 T
0595 A
0596
0597 T
0598 A
0599 P
0600 E
0601 LINE
0602 F
0603 I
0604 L
0605 L
0606 E
0607 D
0608 LINE
0609 LINE
0610 LINE
0611 LINE
0612 LINE
0613 ENDα
0614 SFG     4
```

```
0615 1
0616 0
0617 #REGS
0618 5
0619 0
0620 #REGS
0621 9
0622 STO     R001
0624 NOP
0625 NOP
0626 CLRA÷J
0627 NOP
0628 NOP
0629 RETURN
0630 NOP
0631 NOP
0632 NOP
0633 NOP
0634 NOP
0635 NOP
0636 NOP
0637 NOP
0638 LBL
---- 03
0640 .
0641 0
0642 3
0643 IF X<Y
0644 X⇌Y
0645 ROLL↓
0646 .
0647 0
0648 0
0649 2
0650 5
0651 +⇌-
0652 IF X≥Y
0653 X⇌Y
0654 ROLL↓
0655 RETURN
0656 NOP
0657 NOP
0658 NOP
0659 NOP
0660 NOP
0661 NOP
0662 END
```

TABLE A-2

LISTING OF THE FURNACE THERMAL EFFICIENCY MONITORING CONTROL CODE FOR THE H/P SYSTEM 3051A DATA LOGGER

(Sheet 5 of 5)



```
* FILE     10 *

  484.01966
  11760.189

  493.02039
  12015.191

  493.02064
  11919.191

  516.02090
  12538.192

  511.01996
  12540.192

  489.01906
  11910.191

  511.02207
  12661.192

  507.02656
  12369.192

  530.14099
  12882.195

  466.03256
   9854.196

  438.03137
  10007.192

  466.01048
  10897.193

  644.00091
  12424.199

  279.00091
   7768.189

  119.01300
   6239.175

  575.01516
  15153.193

  566.01703
  14643.193

  511.01888
  13059.191

  493.01948
  12296.190
```

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TABLE A-3
FURNACE THERMAL EFFICIENCY DATA REDUCTION CODE FOR THE H/P 9815 COMPUTER
(Sheet 1 of 7)

```
FILE    -4
TYPE    0
USED    888
MAX     2006

0000 NOP
0001 NOP
0002 NOP
0003 0
0004 #REGS
0005 6
0006 1
0007 #REGS
0008 9
0009 9
0010 9
0011 STO      R019
0013 STO      R014
0015 CFG      1
0016 NOP
0017 PRNTα
0019 L
0020 O
0021 A
0022 D
0023
0024 F
0025 I
0026 L
0027 E
0028 ENDα
0029 NOP
0030 FOR      A→F
0031 2
0032 1
0033 ENTER↑
0034 RCL      A
0035 IF SFG 1
0036 +≠-
0037 PRINT
0038 LOAD
0039 1
0040 9
0041 STO      R010
0043 2
0044 0
0045 STO      R011
0047 1
0048 STO      B
0049 2
0050 0
0051 STO      G
0052 FOR      B→G
0053 2
0054 STO+     R010
0056 STO+     R011
0058 RCL I    R011
0060 STO      H
0061 NOP
0062 INT
0063 0
0064 IF X≥Y
0065 GOTO     0101
0067 ROLL↓
0068 STO      R000
0070 NOP
0071 NOP
0072 NOP
0073 NOP
0074 NOP
0075 NOP
0076 RCL      H
0077 ENTER↑
0078 RCL      R000
0080 -
0081 1
0082 0
0083 0
0084 0
0085 *
0086 STO      H
0087 STO+     R003
0089 ENTER↑
0090 *
0091 STO+     R004
0093 RCL      R015
0095 RCL      H
0096 IF X≥Y
0097 STO      R015
0099 1
0100 STO+     E
0101 RCL I    R010
0103 STO      I
0104 NOP
0105 INT
0106 STO      R012
0108 RCL      I
0109 RCL      R012
0111 -
0112 1
0113 EEX
0114 5
0115 *
0116 STO      R013
0118 RCL      H
0119 0
0120 IF X≥Y
0121 GOTO     0166
0123 RCL      R012
0125 6
0126 0
0127 ÷
0128 ENTER↑
0129 ENTER↑
0130 RCL      R014
0132 6
0133 0
0134 ÷
0135 +
0136 FIX      2
0138 PRNTα
0140 LINE
0141 T
0142 C
0143 Y
0144 C
0145
0146 =
0147
0148 PRINT
0149 ENDα
0150 RCL      R012
0152 RCL      R014
0154 ÷
0155 FIX      4
0157 PRNTα
```

TABLE A-3

FURNACE THERMAL EFFICIENCY DATA REDUCTION CODE FOR THE H/P 9815 COMPUTER

(Sheet 2 of 7)

```
0159 T
0160 R
0161
0162 =
0163
0164 PRINT
0165 ENDα
0166 RCL     R013
0168 STO     R014
0170 RCL     H
0171 0
0172 IF X≥Y
0173 GOTO    0280
0175 RCL     R019
0177 RCL     R012
0179 IF X<Y
0180 STO     R019
0182 RCL     R020
0184 RCL     R012
0186 IF X≥Y
0187 STO     R020
0189 RCL     R012
0191 ENTER↑
0192 ENTER↑
0193 RCL     R014
0195 +
0196 ÷
0197 STO+    R005
0199 ENTER↑
0200 ENTER↑
0201 ENTER↑
0202 *
0203 STO+    R006
0205 *
0206 STO+    R016
0208 *
0209 STO+    R017
0211 RCL     R000
0213 ENTER↑
0214 RCL     R012
0216 ÷
0217 1
0218 4
0219 4
0220 0
0221 0
0222 0
0223 ÷
0224 3
0225 6
0226 0
0227 0
0228 *
0229 1
0230 0
0231 0
0232 *
0233 FIX     2
0235 PRNTα
0237 E
0238 F
0239 F
0240 .
0241
0242 =
0243
0244 PRINT
0245
0246 %
0247 ENDα
0248 1
0249 0
0250 0
0251 ÷
0252 STO+    R008
0254 ENTER↑
0255 *
0256 STO+    R009
0258 SQRT
0259 RCL     R014
0261 *
0262 STO+    R007
0264 RCL     R014
0266 *
0267 STO     R018
0269 RCL     R012
0271 6
0272 0
0273 ÷
0274 STO+    R001
0276 ENTER↑
0277 *
0278 STO+    R002
0280 NEXT    B
0281 NEXT    A
0282 9
0283 9
0284 9
0285 RCL     J
0286 -
0287 IF 0
0288 GOTO    0306
0290 SFG     1
0291 1
0292 STO     A
0293 RCL     J
0294 ENTER↑
0295 *
0296 SQRT
0297 STO     F
0298 9
0299 9
0300 9
0301 STO     J
0302 GOTO    0030
0304 NOP
0305 NOP
0306 RCL     E
0307 FIX     0
0309 PRNTα
0311 LINE
0312 LINE
0313 LINE
0314 LINE
0315 LINE
0316 PRINT
0317
0318 F
0319 I
0320 R
0321 I
0322 N
0323 G
0324 S
0325 ENDα
0326 RCL     R002
0328 STO     D
0329 RCL     R001
0331 STO     C
0332 FIX     1
0334 PRNTα
0336 LINE
0337 PRINT
```

TABLE A-3

FURNACE THERMAL EFFICIENCY DATA REDUCTION CODE FOR THE H/P 9815 COMPUTER

(Sheet 3 of 7)

```
0338
0339 M
0340 I
0341 N
0342 .
0343
0344 O
0345 N
0346 ENDα
0347 MN&SD
0348 FIX      3
0350 PRNTα
0352 LINE
0353 PRINT
0354
0355 M
0356 I
0357 N
0358 .
0359
0360 A
0361 V
0362 E
0363 .
0364 ENDα
0365 X≠Y
0366 FIX      4
0368 PRNTα
0370 PRINT
0371
0372 S
0373 T
0374 D
0375
0376 D
0377 E
0378 V
0379 ENDα
0380 RCL      R019
0382 6
0383 0
0384 ÷
0385 FIX      2
0387 PRNTα
0389 PRINT

0390
0391 M
0392 I
0393 N
0394 .
0395 (
0396 M
0397 I
0398 N
0399 .
0400 )
0401 ENDα
0402 RCL      R020
0404 6
0405 0
0406 ÷
0407 PRNTα
0409 PRINT
0410
0411 M
0412 I
0413 N
0414 .
0415 (
0416 M
0417 A
0418 X
0419 .
0420 )
0421 ENDα
0422 RCL      R005
0424 STO      C
0425 RCL      R006
0427 STO      D
0428 MN&SD
0429 FIX      5
0431 PRNTα
0433 LINE
0434 LINE
0435 PRINT
0436
0437 O
0438 N
0439 /
0440 O
0441 F
0442 F
0443 ENDα
0444 X≠Y
0445 FIX      6
0447 PRNTα
0449 PRINT

0450
0451 S
0452 T
0453 D
0454
0455 D
0456 E
0457 V
0458 ENDα
0459 RCL      R003
0461 STO      C
0462 RCL      R004
0464 STO      D
0465 MN&SD
0466 FIX      2
0468 PRNTα
0470 LINE
0471 LINE
0472 PRINT
0473
0474 C
0475
0476 T
0477 F
0478 G
0479
0480 A
0491 V
0482 E
0483 ENDα
0484 X≠Y
0485 FIX      3
0487 PRNTα
0489 PRINT
0490
0491 S
0492 T
0493 D
0494
0495 D
0496 E
0497 V
0498 ENDα
0499 RCL      R015
0501 FIX      2
0503 PRNTα
0505 PRINT
0506
```

TABLE A-3

FURNACE THERMAL EFFICIENCY DATA REDUCTION CODE FOR THE H/P 9815 COMPUTER

(Sheet 4 of 7)

```
0507 C
0508
0509 (
0510 M
0511 A
0512 X
0513 .
0514 )
0515 ENDα
0516 RCL      R009
0518 STO      C
0519 RCL      R009
0521 STO      D
0522 MN&SD
0523 FIX      5
0525 PRNTα
0527 LINE
0528 LINE
0529 Q
0530 (
0531 O
0532 U
0533 T
0534 /
0535 I
0536 N
0537 )
0538
0539 R
0540 A
0541 T
0542 I
0543 O
0544 LINE
0545 (
0546 A
0547 S
0548 S
0549 U
0550 M
0551 E
0552
0553 1
0554 .
0555 0
0556
0557 G
0558 P
0559 H
0560 )
```

```
0561 LINE
0562
0563 =
0564
0565 PRINT
0566 ENDα
0567 X≠Y
0568 FIX      6
0570 PRNTα
0572
0573
0574
0575 PRINT
0576
0577 S
0578 .
0579
0580 D
0581 .
0582 ENDα
0583 RCL      E
0584 FIX      0
0586 PRNTα
0588 LINE
0589 LINE
0590 LINE
0591 LINE
0592 LINE
0593 LINE
0594 LINE
0595 S
0596 T
0597 A
0598 T
0599 I
0600 S
0601 T
0602 I
0603 C
0604 S
0605 LINE
0606 LINE
0607 N
0608
0609 =
0610
0611 PRINT
0612 ENDα
0613 RCL      R013
0615 PRNTα
```

```
0617 LINE
0618 PRINT
0619
0620 M
0621 I
0622 N
0623 .
0624
0625 O
0626 F
0627 F
0628 ENDα
0629 FIX      2
0631 RCL      R001
0633 PRNTα
0635 LINE
0636 PRINT
0637
0638 M
0639 I
0640 N
0641 .
0642
0643 O
0644 N
0645 ENDα
0646 SCI      8
0648 RCL      R002
0650 PRINT
0651 RCL      R005
0653 PRNTα
0655 LINE
0656 S
0657 U
0658 M
0659
0660 T
0661 R
0662 ENDα
0663 PRINT
0664 RCL      R006
0666 PRINT
0667 RCL      R016
0669 PRINT
0670 RCL      R017
0672 PRINT
0673 RCL      R008
0675 PRNTα
```

TABLE A-3

FURNACE THERMAL EFFICIENCY DATA REDUCTION CODE FOR THE H/P 9815 COMPUTER

(Sheet 5 of 7)

```
0677 LINE
0678 S
0679 U
0680 M
0681
0682 Q
0683
0684 R
0685 A
0686 T
0687 I
0688 O
0689 LINE
0690 PRINT
0691 END∝
0692 RCL      R009
0694 PRINT
0695 RCL      R007
0697 PRNT∝
0699 LINE
0700 S
0701 U
0702 M
0703
0704 T
0705 R
0706 *
0707 Q
0708 R
0709 LINE
0710 PRINT
0711 END∝
0712 RCL      R018
0714 PRINT
0715 RCL      R003
0717 PRNT∝
0719 LINE
0720 S
0721 U
0722 M
0723
0724 T
0725 F
0726 G
0727 LINE
0728 PRINT
0729 END∝
```

```
0730 RCL      R004
0732 PRINT
0733 RCL      R005
0735 ENTER↑
0736 *
0737 +⇌-
0738 ENTER↑
0739 RCL      R006
0741 ENTER↑
0742 RCL      E
0743 *
0744 +
0745 1/X
0746 STO      R015
0748 ENTER↑
0749 RCL      R008
0751 ENTER↑
0752 RCL      R006
0754 *
0755 ENTER↑
0756 RCL      R005
0758 ENTER↑
0759 RCL      R007
0761 *
0762 +⇌-
0763 +
0764 RCL      R015
0766 *
0767 PRNT∝
0769 LINE
0770 LINE
0771 L
0772 E
0773 A
0774 S
0775 T
0776
0777 S
0778 Q
0779 U
0780 A
0781 R
0782 E
0783 S
0784 LINE
```

```
0785 L
0786 I
0787 N
0788 E
0789 A
0790 R
0791
0792 F
0793 I
0794 T
0795 LINE
0796 LINE
0797
0798
0799 X
0800
0801 =
0802
0803 T
0804 O
0805 N
0806 /
0807 T
0808 O
0809 F
0810 F
0811 LINE
0812
0813
0814 Y
0815
0816 =
0817
0818 Q
0819 O
0820 U
0821 T
0822 /
0823 Q
0824 I
0825 N
0826 LINE
0827 LINE
```

TABLE A-3

FURNACE THERMAL EFFICIENCY DATA REDUCTION CODE FOR THE H/P 9815 COMPUTER

(Sheet 6 of 7)

```
0828 Y
0829 =
0830 A
0831 0
0832 +
0833 A
0834 1
0835 *
0836 X
0837 LINE
0838 LINE
0839 A
0840 0
0841
0842 =
0843
0844 PRINT
0845 ENDα
0846 RCL     R005
0848 ENTER↑
0849 RCL     R008
0851 *
0852 +÷-
0853 ENTER↑
0854 RCL     E
0855 ENTER↑
0856 RCL     R007
0858 *
0859 +
0860 RCL     R015
0862 *
0863 PRNTα
0865 LINE
0866 A
0867 1
0868
0869 =
0870
0871 PRINT
0872 ENDα
0873 PRNTα
0875 LINE
0876 LINE
0877 LINE
0878 LINE
0879 LINE
0880 LINE
0881 LINE
0882 LINE
0883 LINE
0884 LINE
0885 LINE
0886 ENDα
0887 END
```

TABLE A-3

FURNACE THERMAL EFFICIENCY DATA REDUCTION CODE FOR THE H/P 9815 COMPUTER

(Sheet 7 of 7)

```
  T-ON WEIGHTED
  EFF. ANALYSIS                     60 FIRINGS

  TR=T(ON)/T(CYC)                 472.9 MIN. ON
       T(OFF)J-1
                                 7.881 MIN. AVE.
 FILES ?                         1.8948 STD DEV
          10                      1.98 MIN.(MIN.)
    TO                           12.17 MIN.(MAX.)
          12
                                  2355 MIN.OFF
 NEG. FILES ?
     NONE
                                 0.22240 ON/CYC
 OIL FLOWRATE =                0.138437 STD DEV
       0.8208 GPH
                               191.47 C TFG AVE
 LOAD                            4.049 STD DEV
     FILE  10                  203.95 C (MAX.)

 TCYC =       40.99          THERM. EFF.(TON)
 TR =         0.2065         (@ 0.8208 GPH)
 EFF. =     74.23 %                =    75.15 %

 TCYC =       42.20
 TR =         0.1947
 EFF. =     73.64 %

 TCYC =       42.99
 TR =         0.2000
 EFF. =     74.01 %

 TCYC =       43.35
 TR =         0.1965
 EFF. =     74.74 %

 TCYC =       41.42
 TR =         0.1968
 EFF. =     74.18 %

 TCYC =       40.28
 TR =         0.2114
 EFF. =     75.47 %
```

TABLE A-4

LISTING OF THE SINGLE INDEPENDENT PARAMETER LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 1 of 7)

```
FILE    -18
TYPE     0
USED    1190
MAX     2008


0000 CFG      1
0001 CFG      2
0002 CFG      3
0003 CFG      4
0004 CLRA→J
0005 0
0006 #REGS
0007 8
0008 1
0009 #REGS
0010 GOSUB    A
0012 PRNTα
0014 LINE
0015 LINE
0016 ENDα
0017 RCL      F
0018 IF +
0019 GOTO     0031
0021 STO      R000
0023 1
0024 0
0025 8
0026 STO      F
0027 RCL      A
0028 IF -
0029 GOTO     0317
0031 FOR      A→F
0032 4
0033 1
0034 RCL      A
0035 IF SFG 1
0036 +⇌-
0037 LOAD
0038 PAUSE
0039 IF SFG 3
0040 GOTO     0061
0042 FIX      0
0044 PRNTα
```

```
0046 LINE
0047 LINE
0048 *
0049 *
0050
0051 F
0052 I
0053 L
0054 E
0055 PRINT
0056
0057 *
0058 *
0059
0060 ENDα
0061 1
0062 STO      B
0063 2
0064 0
0065 STO      G
0066 3
0067 9
0068 STO      R031
0070 4
0071 0
0072 STO      R032
0074 FOR      B→G
0075 2
0076 STO+     R031
0078 STO+     R032
0080 RCL I    R031
0082 ENTER↑
0083 INT
0084 STO      C
0085 -
0086 1
0087 EEX
0088 5
0089 *
0090 STO      R033
0092 IF SFG 4
0093 STO      D
0094 RCL I    R032
0096 ENTER↑
0097 INT
0098 STO      H
0099 -
0100 1
0101 EEX
```

```
0102 3
0103 *
0104 STO      I
0105 RCL      H
0106 RCL      C
0107 IF 0
0108 GOTO     0307
0110 ÷
0111 RCL      E
0112 ÷
0113 1
0114 4
0115 4
0116 0
0117 0
0118 0
0119 ÷
0120 3
0121 6
0122 0
0123 0
0124 *
0125 STO      H
0126 1
0127 0
0128 0
0129 *
0130 RCL      R039
0132 IF X≥Y
0133 GOTO     0304
0135 ROLL↓
0136 RCL      R040
0138 IF X<Y
0139 GOTO     0304
0141 RCL      C
0142 ENTER↑
0143 ENTER↑
0144 RCL      D
0145 IF 0
0146 GOTO     0307
0148 IF CFG 2
0149 +
0150 ÷
0151 STO      R034
0153 RCL      R037
0155 IF X≥Y
0156 GOTO     0304
0158 ROLL↓
0159 RCL      R038
```

TABLE A-4
LISTING OF THE SINGLE INDEPENDENT PARAMETER LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER
(Sheet 2 of 7)

```
0161 IF X<Y
0162 GOTO    0304
0164 ROLL↓
0165 STO+    R001
0167 1/X
0168 STO+    R005
0170 ENTER↑
0171 *
0172 STO+    R006
0174 1/X
0175 STO+    R002
0177 RCL     R034
0179 LN
0180 STO+    R003
0182 ENTER↑
0183 *
0184 STO+    R004
0186 RCL     H
0187 STO+    R007
0189 1/X
0190 STO+    R011
0192 ENTER↑
0193 *
0194 STO+    R012
0196 1/X
0197 STO+    R008
0199 RCL     H
0200 LN
0201 STO+    R009
0203 ENTER↑
0204 *
0205 STO+    R010
0207 RCL     H
0208 RCL     R034
0210 *
0211 STO+    R013
0213 1/X
0214 STO+    R018
0216 RCL     H
0217 RCL     R034
0219 ÷
0220 STO+    R016
0222 1/X
0223 STO+    R017
0225 RCL     H
0226 LN
0227 ENTER↑
0228 ENTER↑
0229 RCL     R034
```

```
0231 *
0232 STO+    R014
0234 ROLL↓
0235 RCL     R034
0237 LN
0238 *
0239 STO+    R015
0241 1
0242 STO+    R030
0244 IF SFG 3
0245 GOTO    0304
0247 RCL     C
0248 RCL     D
0249 +
0250 6
0251 0
0252 ÷
0253 FIX     2
0255 PRNTα
0257 LINE
0258
0259
0260 T
0261 C
0262 Y
0263 C
0264
0265 =
0266 PRINT
0267 ENDα
0268 RCL     R034
0270 FIX     4
0272 PRNTα
0274
0275
0276
0277
0278 T
0279 R
0280
0281 =
0282
0283 PRINT
0284 ENDα
0285 RCL     H
```

```
0286 1
0287 0
0288 0
0289 *
0290 FIX     2
0292 PRNTα
0294 E
0295 F
0296 F
0297 .
0298
0299 =
0300
0301 PRINT
0302 %
0303 ENDα
0304 RCL     R033
0306 STO     D
0307 NEXT    B
0308 IF SFG 3
0309 GOTO    0316
0311 PRNTα
0313 LINE
0314 LINE
0315 ENDα
0316 NEXT    A
0317 RCL     R000
0319 IF 0
0320 GOTO    0332
0322 +⇌-
0323 STO     F
0324 1
0325 STO     A
0326 0
0327 STO     R000
0329 SFG     1
0330 GOTO    0031
0332 CFG     2
0333 RCL     R001
0335 RCL     R030
0337 FIX     0
0339 PRNTα
0341 LINE
0342 LINE
0343 LINE
0344 LINE
```

TABLE A-4

LISTING OF THE SINGLE INDEPENDENT PARAMETER LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 3 of 7)

```
0345 S
0346 T
0347 A
0348 T
0349 I
0350 S
0351 T
0352 I
0353 C
0354 S
0355 LINE
0356 PRINT
0357
0358 F
0359 I
0360 R
0361 I
0362 N
0363 G
0364 S
0365 ENDα
0366 IF 0
0367 GOTO     0710
0369 ÷
0370 STO      R035
0372 STO      R022
0374 FIX      3
0376 PRNTα
0378 A
0379 V
0380 E
0381 R
0382 A
0383 G
0384 E
0385 LINE
0386 T
0387 R
0388
0389 =
0390
0391 PRINT
0392 ENDα
0393 RCL      R002
0395 STO      R024
0397 GOSUB    B
0399 RCL      R007
```

```
0401 RCL      R030
0403 ÷
0404 STO      R036
0406 STO      R022
0408 1
0409 0
0410 0
0411 *
0412 FIX      2
0414 PRNTα
0416 LINE
0417 E
0418 F
0419 F
0420 .
0421
0422 =
0423
0424 PRINT
0425 %
0426 ENDα
0427 RCL      R008
0429 STO      R024
0431 GOSUB    B
0433 PRNTα
0435 (
0436 /
0437 1
0438 0
0439 0
0440 )
0441 ENDα
0442 RCL      R035
0444 STO      R022
0446 RCL      R036
0448 STO      R025
0450 RCL      R001
0452 STO      R023
0454 RCL      R002
0456 STO      R024
0458 RCL      R007
0460 STO      R026
0462 RCL      R013
0464 STO      R027
0466 RCL      R008
0468 STO      R028
0470 PRNTα
0472 LINE
0473 LINE
```

```
0474 LINE
0475 Y
0476
0477 =
0478
0479 A
0480
0481 +
0482
0483 B
0484 *
0485 X
0486 ENDα
0487 GOSUB    C
0489 RCL      R009
0491 STO      R026
0493 RCL      R030
0495 ÷
0496 STO      R025
0498 RCL      R014
0500 STO      R027
0502 RCL      R010
0504 STO      R028
0506 PRNTα
0508 LINE
0509 LINE
0510 LINE
0511 Y
0512
0513 =
0514
0515 A
0516 *
0517 E
0518 X
0519 P
0520 (
0521 B
0522 *
0523 X
0524 )
0525 ENDα
0526 SFG      2
0527 GOSUB    C
0529 RCL      R003
0531 STO      R023
0533 RCL      R030
0535 ÷
0536 STO      R022
```

TABLE A-4

LISTING OF THE SINGLE INDEPENDENT PARAMETER LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 4 of 7)

```
0538 RCL     R004
0540 STO     R024
0542 RCL     R015
0544 STO     R027
0546 PRNTα
0548 LINE
0549 LINE
0550 LINE
0551 Y
0552
0553 =
0554
0555 A
0556 *
0557 X
0558 *
0559 *
0560 B
0561 ENDα
0562 GOSUB   C
0564 CFG     2
0565 RCL     R005
0567 STO     R023
0569 RCL     R030
0571 ÷
0572 STO     R022
0574 RCL     R006
0576 STO     R024
0578 RCL     R007
0580 STO     R026
0582 RCL     R036
0584 STO     R025
0586 RCL     R016
0588 STO     R027
0590 RCL     R008
0592 STO     R028
0594 PRNTα
0596 LINE
0597 LINE
0598 LINE
0599 Y
0600
0601 =
0602
0603 A
0604
0605 +
0606
0607 B
0608 /
0609 X
0610 ENDα
```

```
0611 GOSUB   C
0613 RCL     R035
0615 STO     R022
0617 RCL     R001
0619 STO     R023
0621 RCL     R002
0623 STO     R024
0625 RCL     R011
0627 STO     R026
0629 RCL     R030
0631 ÷
0632 STO     R025
0634 RCL     R017
0636 STO     R027
0638 RCL     R012
0640 STO     R028
0642 PRNTα
0644 LINE
0645 LINE
0646 LINE
0647 Y
0648
0649 =
0650
0651 1
0652 /
0653 (
0654 A
0655 +
0656 B
0657 *
0658 X
0659 )
0660 ENDα
0661 GOSUB   C
0663 RCL     R005
0665 STO     R023
0667 RCL     R030
0669 ÷
0670 STO     R022
0672 RCL     R006
0674 STO     R024
0676 RCL     R018
0678 STO     R027
0680 PRNTα
0682 LINE
0683 LINE
0684 LINE
```

```
0685 Y
0686
0687 =
0688
0689 X
0690 /
0691 (
0692 A
0693 *
0694 X
0695 +
0696 B
0697 )
0698 ENDα
0699 GOSUB   C
0701 PRNTα
0703 LINE
0704 LINE
0705 LINE
0706 LINE
0707 LINE
0708 LINE
0709 ENDα
0710 STOP
0711 NOP
0712 NOP
0713 NOP
0714 NOP
0715 LBL
---- A
0717 PRNTα
0719 LINE
0720 LINE
0721 LINE
0722 LINE
0723 C
0724
0725 U
0726
0727 R
0728
0729 V
0730
0731 E
0732
0733 F
0734
0735 I
0736
0737 T
```

TABLE A-4

LISTING OF THE SINGLE INDEPENDENT PARAMETER LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 5 of 7)

```
0738 LINE
0739
0740
0741
0742
0743 A
0744 N
0745 A
0746 L
0747 Y
0748 S
0749 I
0750 S
0751 LINE
0752
0753
0754
0755 (
0756 H
0757 /
0758 P
0759
0760 D
0761 A
0762 T
0763 A
0764 )
0765 LINE
0766 LINE
0767 ENDα
0768 IF SFG 2
0769 GOTO    0791
0771 PRNTα
0773 T
0774 R
0775 =
0776 T
0777 (
0778 O
0779 N
0780 )
0781 /
0782 T
0783 (
0784 C
0785 Y
0786 C
0787 )
0788 ENDα
```

```
0789 GOTO    0809
0791 PRNTα
0793 T
0794 R
0795 =
0796 T
0797 (
0798 O
0799 N
0800 )
0801 /
0802 T
0803 (
0804 O
0805 F
0806 F
0807 )
0808 ENDα
0809 IF SFG 4
0810 GOTO    0833
0812 PRNTα
0814
0815
0816
0817
0818
0819
0820
0821
0822
0823
0824
0825
0826
0827 J
0828 -
0829 1
0830 ENDα
0831 GOTO    0852
0833 PRNTα
0835
0836
0837
0838
```

```
0839
0840
0841
0842
0843
0844
0845
0846
0847
0848
0849
0850 J
0851 ENDα
0852 FIX         0
0854 PRNTα
0856 LINE
0857 I
0858 N
0859 P
0860 U
0861 T
0862
0863 D
0864 A
0865 T
0866 A
0867 LINE
0868 LINE
0869 E
0870 V
0871 A
0872 L
0873 U
0874 A
0875 T
0876 E
0877 LINE
0878 LINE
0879 F
0880 I
0881 L
0882 E
0883 S
0884 ENDα
0885 STOP
0886 STO       A
0887 PRINT
0888 PRNTα
```

TABLE A-4

LISTING OF THE SINGLE INDEPENDENT PARAMETER LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 6 of 7)

```
0890
0891
0892 T
0893 O
0894 ENDα
0895 STOP
0896 STO    F
0897 PRINT
0898 FIX    4
0900 PRNTα
0902 LINE
0903 O
0904 I
0905 L
0906
0907 F
0908 L
0909 O
0910 W
0911 R
0912 A
0913 T
0914 E
0915 ENDα
0916 STOP
0917 STO    E
0918 PRINT
0919 PRNTα
0921 LINE
0922 T
0923 R
0924 ENDα
0925 STOP
0926 STO    R037
0928 PRINT
0929 PRNTα
0931
0932
0933
0934 T
0935 O
0936 ENDα
0937 STOP
0938 STO    R038
0940 PRINT
0941 FIX    1
0943 PRNTα
```

```
0945 LINE
0946 E
0947 F
0948 F
0949 I
0950 C
0951 I
0952 E
0953 N
0954 C
0955 Y
0956 ,
0957
0958 %
0959 ENDα
0960 STOP
0961 STO    R039
0963 PRINT
0964 PRNTα
0966
0967
0968
0969 T
0970 O
0971 ENDα
0972 STOP
0973 STO    R040
0975 PRINT
0976 PRNTα
0978 LINE
0979 P
0980 R
0981 I
0982 N
0983 T
0984
0985 E
0986 V
0987 E
0988 R
0989 Y
0990
0991 R
0992 U
0993 N
0994 ?
0995
0996
```

```
0997 (
0998 0
0999
1000 =
1001
1002 N
1003 O
1004 )
1005 ENDα
1006 CLEAR
1007 STOP
1008 IF 0
1009 SFG    3
1010 FIX    0
1012 PRNTα
1014 PRINT
1015 LINE
1016 LINE
1017 LINE
1018 ENDα
1019 RETURN
1020 NOP
1021 NOP
1022 NOP
1023 LBL
---- B
1025 RCL    R024
1027 RCL    R022
1029 ENTER↑
1030 *
1031 RCL    R030
1033 ÷
1034 +≑-
1035 +
1036 RCL    R030
1038 1
1039 -
1040 ÷
1041 SQRT
1042 FIX    4
1044 PRNTα
1046
1047 S
1048 .
1049 D
1050 .
1051
1052 =
1053
1054 PRINT
1055 ENDα
```

TABLE A-4

LISTING OF THE SINGLE INDEPENDENT PARAMETER LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

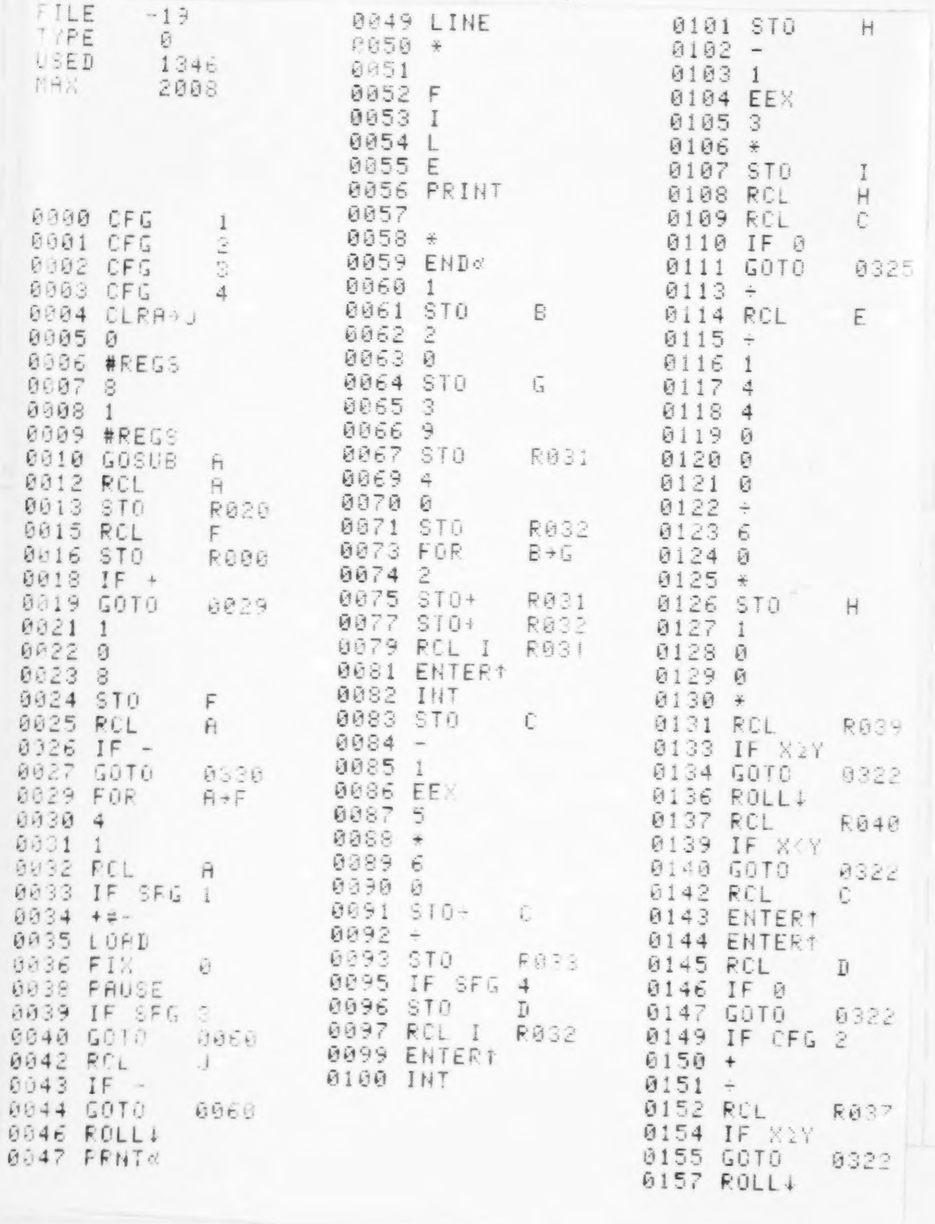
(Sheet 7 of 7)

```
1056 RETURN
1057 NOP
1058 NOP
1059 NOP
1060 NOP
1061 LBL
---- C
1063 RCL     R023
1065 ENTER↑
1066 *
1067 RCL     R030
1069 ÷
1070 +⇌-
1071 RCL     R024
1073 +
1074 1/X
1075 ENTER↑
1076 ENTER↑
1077 RCL     R023
1079 RCL     R026
1081 *
1082 RCL     R030
1084 ÷
1085 +⇌-
1086 RCL     R027
1088 +
1089 *
1090 STO     R029
1092 RCL     R022
1094 *
1095 +⇌-
1096 RCL     R025
1098 +
1099 IF SFG 2
1100 e↑X
1101 SCI     7
1103 PRNTα
1105 LINE
1106 A
1107 =
1108 PRINT
1109 ENDα
1110 RCL     R029
1112 PRNTα
1114 LINE
1115 B
1116 =
1117 PRINT
1118 ENDα
1119 RCL     R023
1121 ENTER↑
1122 *
1123 RCL     R030
1125 ÷
1126 +⇌-
1127 RCL     R024
1129 +
1130 ENTER↑
1131 RCL     R026
1133 ENTER↑
1134 *
1135 RCL     R030
1137 ÷
1138 +⇌-
1139 RCL     R028
1141 +
1142 *
1143 1/X
1144 RCL     R023
1146 RCL     R026
1148 *
1149 RCL     R030
1151 ÷
1152 +⇌-
1153 RCL     R027
1155 +
1156 ENTER↑
1157 *
1158 *
1159 FIX     8
1161 PRNTα
1163 LINE
1164 I
1165 N
1166 D .
1167 E
1168 X
1169
1170 O
1171 F
1172
1173 D
1174 E
1175 T
1176 E
1177 R
1178 M
1179 .
1180 ENDα
1181 PRINT
1182 ENDα
1183 RETURN
1184 NOP
1185 NOP
1186 NOP
1187 NOP
1188 NOP
1189 END
```

TABLE A-5

LISTING OF THE TWO INDEPENDENT PARAMETERS LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 1 of 9)



```
FILE    -19
TYPE    0
USED    1346
MAX     2008



0000 CFG     1
0001 CFG     2
0002 CFG     3
0003 CFG     4
0004 CLRA→J
0005 0
0006 #REGS
0007 8
0008 1
0009 #REGS
0010 GOSUB   A
0012 RCL     A
0013 STO     R020
0015 RCL     F
0016 STO     R000
0018 IF +
0019 GOTO    0029
0021 1
0022 0
0023 8
0024 STO     F
0025 RCL     A
0326 IF -
0027 GOTO    0330
0029 FOR     A→F
0030 4
0031 1
0032 RCL     A
0033 IF SFG 1
0034 +⇌-
0035 LOAD
0036 FIX     0
0038 PAUSE
0039 IF SFG 3
0040 GOTO    0060
0042 RCL     J
0043 IF -
0044 GOTO    0060
0046 ROLL↓
0047 PRNT∝
0049 LINE
0050 *
0051
0052 F
0053 I
0054 L
0055 E
0056 PRINT
0057
0058 *
0059 END∝
0060 1
0061 STO     B
0062 2
0063 0
0064 STO     G
0065 3
0066 9
0067 STO     R031
0069 4
0070 0
0071 STO     R032
0073 FOR     B→G
0074 2
0075 STO+    R031
0077 STO+    R032
0079 RCL I   R031
0081 ENTER↑
0082 INT
0083 STO     C
0084 -
0085 1
0086 EEX
0087 5
0088 *
0089 6
0090 0
0091 STO÷    C
0092 ÷
0093 STO     R033
0095 IF SFG 4
0096 STO     D
0097 RCL I   R032
0099 ENTER↑
0100 INT
0101 STO     H
0102 -
0103 1
0104 EEX
0105 3
0106 *
0107 STO     I
0108 RCL     H
0109 RCL     C
0110 IF 0
0111 GOTO    0325
0113 ÷
0114 RCL     E
0115 ÷
0116 1
0117 4
0118 4
0119 0
0120 0
0121 0
0122 ÷
0123 6
0124 0
0125 *
0126 STO     H
0127 1
0128 0
0129 0
0130 *
0131 RCL     R039
0133 IF X≥Y
0134 GOTO    0322
0136 ROLL↓
0137 RCL     R040
0139 IF X<Y
0140 GOTO    0322
0142 RCL     C
0143 ENTER↑
0144 ENTER↑
0145 RCL     D
0146 IF 0
0147 GOTO    0322
0149 IF CFG 2
0150 +
0151 ÷
0152 RCL     R037
0154 IF X≥Y
0155 GOTO    0322
0157 ROLL↓
```

TABLE A-5

LISTING OF THE TWO INDEPENDENT PARAMETERS LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 2 of 9)

```
0158 RCL     R038
0160 IF X<Y
0161 GOTO    0322
0163 ROLL↓
0164 1/X
0165 STO     R034
0167 RCL     C
0168 RCL     R027
0170 IF X≥Y
0171 GOTO    0322
0173 RCL     C
0174 RCL     R028
0176 IF X<Y
0177 GOTO    0322
0179 RCL     C
0180 1/X
0181 STO     R029
0183 RCL     J
0184 IF +
0185 GOTO    0238
0187 ROLL↓
0188 STO+    R003
0190 ENTER↑
0191 *
0192 STO+    R005
0194 RCL     R034
0196 ENTER↑
0197 ENTER↑
0198 STO+    R002
0200 *
0201 STO+    R004
0203 ROLL↓
0204 RCL     R029
0206 *
0207 STO+    R006
0209 RCL     H
0210 STO+    R007
0212 RCL     R034
0214 *
0215 STO+    R008
0217 RCL     H
0218 RCL     R029
0220 *
0221 STO+    R009
0223 RCL     C
0224 STO+    R012
0226 RCL     H
0227 *
0228 STO+    R011
```

```
0230 RCL     D
0231 STO+    R013
0233 1
0234 STO+    R001
0236 GOTO    0322
0238 IF SFG 3
0239 GOTO    0299
0241 RCL     R034
0243 1/X
0244 FIX     4
0246 PRNTα
0248 LINE
0249
0250
0251 T
0252 R
0253
0254 =
0255
0256 PRINT
0257
0258
0259 ENDα
0260 RCL     R029
0262 1/X
0263 FIX     2
0265 PRNTα
0267 T
0268 B
0269
0270 =
0271
0272 PRINT
0273
0274 M
0275 I
0276 N
0277 .
0278 ENDα
0279 RCL     H
0280 1
0281 0
0282 0
0283 *
0284 FIX     2
0286 PRNTα
```

```
0288 E
0289 F
0290 F
0291 .
0292
0293 =
0294
0295 PRINT
0296 %
0297 ENDα
0298 GOSUB   B
0300 IF SFG 3
0301 GOTO    0322
0303 RCL     R023
0305 1
0306 0
0307 0
0308 *
0309 PRNTα
0311 (
0312 C
0313 A
0314 L
0315 C
0316 )
0317
0318 =
0319 PRINT
0320 %
0321 ENDα
0322 RCL     R033
0324 STO     D
0325 NEXT    B
0326 NEXT    A
0327 IF SFG 1
0328 GOTO    0347
0330 RCL     R000
0332 IF +
0333 GOTO    0347
0335 +⇌-
0336 STO     F
0337 1
0338 STO     A
0339 RCL     R020
0341 +⇌-
0342 IF +
0343 STO     A
0344 SFG     1
0345 GOTO    0029
0347 RCL     J
```

TABLE A-5

LISTING OF THE TWO INDEPENDENT PARAMETERS LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 3 of 9)

```
0348 IF +
0349 GOTO     0848
0351 1
0352 0
0353 0
0354 STO      J
0355 RCL      R001
0357 FIX      0
0359 PRNTα
0361 LINE
0362 LINE
0363 LINE
0364 LINE
0365 *
0366 *
0367
0368 S
0369 T
0370 A
0371 T
0372 I
0373 S
0374 T
0375 I
0376 C
0377 S
0378
0379 *
0380 *
0381 LINE
0382 LINE
0383 PRINT
0384
0385 F
0386 I
0387 R
0388 I
0389 N
0390 G
0391 S
0392 ENDα
0393 IF 0
0394 GOTO     0912
0396 RCL      R012
0398 FIX      1
0400 PRNTα
0402 LINE
0403 LINE
0404 T
0405 O
0406 T
0407 A
0408 L
0409 S
0410 :
0411 LINE
0412 LINE
0413
0414 T
0415 B
0416
0417 =
0418 PRINT
0419 ENDα
0420 RCL      R013
0422 PRNTα
0424 LINE
0425 T
0426 O
0427 F
0428 F
0429 =
0430 PRINT
0431 ENDα
0432 RCL      R002
0434 RCL      R001
0436 ÷
0437 STO      R035
0439 1/X
0440 FIX      4
0442 PRNTα
0444 LINE
0445 LINE
0446 A
0447 V
0448 E
0449 R
0450 A
0451 G
0452 E
0453 S
0454 :
0455 ENDα
0456 FIX      4
0458 PRNTα
0460 LINE
0461
0462
0463
0464 T
0465 R
0466
0467 =
0468
0469 PRINT
0470 ENDα
0471 RCL      R003
0473 RCL      R001
0475 ÷
0476 STO      R030
0478 1/X
0479 FIX      3
0481 PRNTα
0483 LINE
0484 T
0485 B
0486
0487 =
0488
0489 PRINT
0490
0491 M
0492 I
0493 N
0494 .
0495 ENDα
0496 RCL      R007
0498 RCL      R001
0500 ÷
0501 STO      R036
0503 RCL      J
0504 *
0505 FIX      2
0507 PRNTα
0509 LINE
0510 E
0511 F
0512 F
0513 .
0514
0515 =
0516
0517 PRINT
0518 %
0519 ENDα
```

TABLE A-5

LISTING OF THE TWO INDEPENDENT PARAMETERS LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 4 of 9)

```
0520 RCL     R011
0522 RCL     R012
0524 ÷
0525 RCL     J
0526 *
0527 PRNTα
0529
0530 F
0531 (
0532 T
0533 B
0534 )
0535
0536 =
0537 PRINT
0538 %
0539 LINE
0540 LINE
0541 LINE
0542 *
0543
0544 C
0545 O
0546 E
0547 F
0548 F
0549 I
0550 C
0551 I
0552 E
0553 N
0554 T
0555 S
0556
0557 *
0558 LINE
0559 LINE
0560 Y
0561 =
0562 B
0563 0
0564 +
0565 B
0566 1
0567 *
0568 X
0569 1
0570 +
0571 B
0572 2
0573 *
0574 X
0575 2
0576 ENDα
```

```
0577 RCL     R001
0579 RCL     R004
0581 RCL     R005
0583 *
0584 *
0585 RCL     R002
0587 RCL     R003
0589 RCL     R006
0591 *
0592 *
0593 2
0594 *
0595 +
0596 RCL     R003
0598 ENTER↑
0599 *
0600 RCL     R004
0602 *
0603 -
0604 RCL     R002
0606 ENTER↑
0607 *
0608 RCL     R005
0610 *
0611 -
0612 RCL     R006
0614 ENTER↑
0615 *
0616 RCL     R001
0618 *
0619 -
0620 STO     R010
0622 RCL     R004
0624 RCL     R005
0626 RCL     R007
0628 *
0629 *
0630 RCL     R003
0632 RCL     R006
0634 RCL     R008
0636 *
0637 *
0638 +
0639 RCL     R002
0641 RCL     R006
0643 RCL     R009
0645 *
0646 *
0647 +
0648 RCL     R006
0650 ENTER↑
```

```
0651 *
0652 RCL     R007
0654 *
0655 -
0656 RCL     R002
0658 RCL     R005
0660 RCL     R008
0662 *
0663 *
0664 -
0665 RCL     R003
0667 RCL     R004
0669 RCL     R009
0671 *
0672 *
0673 -
0674 RCL     R010
0676 ÷
0677 STO     R024
0679 RCL     J
0680 *
0681 FIX     7
0683 PRNTα
0685 LINE
0686 LINE
0687 B
0688 0
0689
0690 =
0691 PRINT
0692 ENDα
0693 RCL     R001
0695 RCL     R005
0697 RCL     R008
0699 *
0700 *
0701 RCL     R002
0703 RCL     R003
0705 RCL     R009
0707 *
0708 *
0709 +
0710 RCL     R003
0712 RCL     R006
0714 RCL     R007
0716 *
0717 *
0718 +
0719 RCL     R001
0721 RCL     R006
```

TABLE A-5

LISTING OF THE TWO INDEPENDENT PARAMETERS LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 5 of 9)

```
0723 RCL     R009
0725 *
0726 *
0727 -
0728 RCL     R002
0730 RCL     R005
0732 RCL     R007
0734 *
0735 *
0736 -
0737 RCL     R003
0739 ENTER↑
0740 *
0741 RCL     R008
0743 *
0744 -
0745 RCL     R010
0747 ÷
0748 STO     R025
0750 RCL     J
0751 *
0752 PRNTα
0754 LINE
0755 LINE
0756 B
0757 1
0758
0759 =
0760 PRINT
0761 ENDα
0762 RCL     R001
0764 RCL     R004
0766 RCL     R009
0768 *
0769 *
0770 RCL     R002
0772 RCL     R006
0774 RCL     R007
0776 *
0777 *
0778 +
0779 RCL     R002
0781 RCL     R003
0783 RCL     R008
0785 *
0786 *
0787 +
0788 RCL     R001
0790 RCL     R006
```

```
0792 RCL     R008
0794 *
0795 *
0796 -
0797 RCL     R002
0799 ENTER↑
0800 *
0801 RCL     R009
0803 *
0804 -
0805 RCL     R003
0807 RCL     R004
0809 RCL     R007
0811 *
0812 *
0813 -
0814 RCL     R010
0816 ÷
0817 STO     R026
0819 RCL     J
0820 *
0821 PRNTα
0823 LINE
0824 LINE
0825 B
0826 2
0827
0828 =
0829 PRINT
0830 LINE
0831 LINE
0832 LINE
0833 ENDα
0834 0
0835 STO     R021
0837 STO     R022
0839 CFG     1
0840 RCL     R000
0842 STO     F
0843 RCL     R020
0845 STO     A
0846 GOTO    0015
0848 RCL     R021
0850 RCL     R022
0852 IF 0
0853 GOTO    0912
0855 ÷
0856 +⇄-
0857 1
0858 +
0859 FIX     7
0861 PRNTα
```

```
0863 LINE
0864 I
0865 N
0866 D
0867 E
0868 X
0869
0870 O
0871 F
0872
0873 D
0874 E
0875 T
0876 E
0877 R
0878 M
0879 .
0880 PRINT
0881 LINE
0882 ENDα
0883 RCL     R021
0885 RCL     R001
0887 ÷
0888 SQRT
0889 RCL     J
0890 *
0891 FIX     4
0893 PRNTα
0895 LINE
0896 S
0897 T
0898 D
0899
0900 D
0901 E
0902 V
0903 =
0904 PRINT
0905 %
0906 LINE
0907 LINE
0908 LINE
0909 LINE
0910 LINE
0911 ENDα
0912 STOP
0913 NOP
0914 LBL
---- A
0916 PRNTα
```

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TABLE A-5

LISTING OF THE TWO INDEPENDENT PARAMETERS LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 6 of 9)

```
0918 LINE
0919 LINE
0920 LINE
0921 LINE
0922 *
0923
0924 M
0925
0926 U
0927
0928 L
0929
0930 F
0931
0932 I
0933
0934 T
0935
0936 *
0937 LINE
0938
0939
0940
0941
0942 A
0943 N
0944 A
0945 L
0946 Y
0947 S
0948 I
0949 S
0950 LINE
0951 LINE
0952
0953
0954
0955 X
0956 1
0957
0958 =
0959
0960 1
0961 /
0962 T
0963 R
0964 LINE
0965 LINE
0966
0967
0968
0969 X
0970 2
0971
0972 =
0973
0974 1
0975 /
0976 T
0977 B
0978 ENDα
0979 IF SFG 2
0980 GOTO    1003
0982 PRNTα
0984 LINE
0985 T
0986 R
0987 =
0988 T
0989 (
0990 O
0991 N
0992 )
0993 /
0994 T
0995 (
0996 C
0997 Y
0998 C
0999 )
1000 ENDα
1001 GOTO    1022
1003 PRNTα
1005 LINE
1006 T
1007 R
1008 =
1009 T
1010 (
1011 O
1012 N
1013 )
1014 /
1015 T
1016 (
1017 O
1018 F
1019 F
1020 )
1021 ENDα
1022 IF SFG 4
1023 GOTO    1046
1025 PRNTα
1027
1028
1029
1030
1031
1032
1033
1034
1035
1036
1037
1038
1039
1040 J
1041 -
1042 1
1043 ENDα
1044 GOTO    1064
1046 PRNTα
1048
1049
1050
1051
1052
1053
1054
1055
1056
1057
1058
1059
1060
1061
1062 J
1063 ENDα
1064 FIX     0
1066 PRNTα
1068 LINE
1069
1070
1071 T
1072 B
1073
1074 =
1075
1076 T
```

TABLE A-5

LISTING OF THE TWO INDEPENDENT PARAMETERS LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 7 of 9)

```
1077 (
1078 B
1079 U
1080 R
1081 N
1082 )
1083 LINE
1084 LINE
1085 LINE
1086 I
1087 N
1088 P
1089 U
1090 T
1091
1092 D
1093 A
1094 T
1095 A
1096 :
1097 LINE
1098 LINE
1099 E
1100 V
1101 A
1102 L
1103 U
1104 A
1105 T
1106 E
1107
1108 -
1109 LINE
1110 LINE
1111 F
1112 I
1113 L
1114 E
1115 S
1116 ENDα
1117 STOP
1118 STO     A
1119 PRINT
1120 PRNTα
1122
1123
1124
1125
1126 T
1127 O
1128 ENDα
```

```
1129 STOP
1130 STO     F
1131 PRINT
1132 FIX     4
1134 PRNTα
1136 LINE
1137 O
1138 I
1139 L
1140
1141 F
1142 L
1143 O
1144 W
1145 R
1146 A
1147 T
1148 E
1149 ENDα
1150 STOP
1151 STO     E
1152 PRINT
1153 PRNTα
1155 LINE
1156 T
1157 R
1158 ENDα
1159 STOP
1160 STO     R037
1162 PRINT
1163 PRNTα
1165
1166
1167
1168 T
1169 O
1170 ENDα
1171 STOP
1172 STO     R038
1174 PRINT
1175 PRNTα
1177 LINE
1178 T
1179 B
1180 ,
1181
1182 M
1183 I
1184 N
1185 .
1186 ENDα
```

```
1187 STOP
1188 STO     R027
1190 FIX     2
1192 PRINT
1193 PRNTα
1195
1196
1197
1198 T
1199 O
1200 ENDα
1201 STOP
1202 STO     R028
1204 PRINT
1205 FIX     1
1207 PRNTα
1209 LINE
1210 E
1211 F
1212 F
1213 I
1214 C
1215 I
1216 E
1217 N
1218 C
1219 Y
1220 ,
1221
1222 %
1223 ENDα
1224 STOP
1225 STO     R039
1227 PRINT
1228 PRNTα
1230
1231
1232
1233 T
1234 O
1235 ENDα
1236 STOP
1237 STO     R040
1239 PRINT
1240 PRNTα
1242 LINE
```

TABLE A-5

LISTING OF THE TWO INDEPENDENT PARAMETERS LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 8 of 9)

```
1243 P
1244 R
1245 I
1246 N
1247 T
1248
1249 E
1250 V
1251 E
1252 R
1253 Y
1254
1255 R
1256 U
1257 N
1258 ?
1259
1260 (
1261 N
1262 O
1263
1264 E
1265 N
1266 T
1267 R
1268 Y
1269
1270 =
1271
1272 N
1273 O
1274 )
1275 ENDα
1276 STOP
1277 IF CFG 7
1278 GOTO    1292
1280 SFG     3
1281 PRNTα
1283
1284
1285
1286
1287 N
1288 O
1289 ENDα
1290 GOTO    1301
1292 PRNTα
```

```
1294
1295
1296
1297 Y
1298 E
1299 S
1300 ENDα
1301 1
1302 +⇄-
1303 STO      J
1304 PRNTα
1306 LINE
1307 LINE
1308 LINE
1309 ENDα
1310 RETURN
1311 LBL
---- B
1313 RCL     R029
1315 RCL     R026
1317 *
1318 RCL     R034
1320 RCL     R025
1322 *
1323 +
1324 RCL     R024
1326 +
1327 STO     R023
1329 +⇄-
1330 RCL     H
1331 +
1332 ENTER↑
1333 *
1334 STO+    R021
1336 RCL     H
1337 RCL     R036
1339 -
1340 ENTER↑
1341 *
1342 STO+    R022
1344 RETURN
1345 END
```

TABLE A-5

LISTING OF THE TWO INDEPENDENT PARAMETERS LEAST-SQUARES CURVEFITTING CODE FOR THE H/P 9815 COMPUTER

(Sheet 9 of 9)

```
* M U L F I T *
   ANALYSIS

   X1 = 1/TR

   X2 = 1/TB

TR=T(ON)/T(CYC)
            J-1

  TB = T(BURN)

INPUT DATA:

EVALUATE -

FILES
          10
    TO
          12

OIL FLOWRATE
      0.8208

TR
     0.0100
   TO
     0.9900

TB, MIN.
       0.50
   TO
   10000.00

EFFICIENCY, %
       10.0
   TO
     1000.0

PRINT EVERY RUN?
 (NO ENTRY = NO)
  YES
```

```
** STATISTICS **

       59 FIRINGS


TOTALS:

 TB =        472.9

TOFF=       2354.6

AVERAGES:

   TR =    0.1678

TB =  7.313 MIN.

EFF. =     78.79%
 F(TB) =   75.15%

* COEFFICIENTS *

Y=B0+B1*X1+B2*X2

B0 =  35.8842875

B1 =  -0.5859397

B2 = 339.3172093
```

```
* FILE       10 *

  TR =  0.2397
TB =   8.07 MIN.
EFF. =     74.01%
(CALC) =  75.50%

  TR =  0.2005
TB =   8.22 MIN.
EFF. =     74.23%
(CALC) =  74.26%

  TR =  0.1947
TB =   8.22 MIN.
EFF. =     73.64%
(CALC) =  74.17%

  TR =  0.2000
TB =   8.60 MIN.
EFF. =     74.01%
(CALC) =  72.41%

  TR =  0.1965
TB =   8.52 MIN.
EFF. =     74.74%
(CALC) =  72.74%

  TR =  0.1968
TB =   8.15 MIN.
EFF. =     74.18%
(CALC) =  74.54%

  TR =  0.2114
TB =   8.52 MIN.
EFF. =     75.47%
(CALC) =  72.95%

  TR =  0.1868
TB =   8.45 MIN.
EFF. =     74.31%
(CALC) =  72.90%

  TR =  0.1664
TB =   8.83 MIN.
EFF. =     74.03%
(CALC) =  70.78%

  TR =  0.0320
TB =   7.77 MIN.
EFF. =     64.41%
(CALC) =  61.26%
```

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APPENDIX B

FUEL OIL COMPOSITION ANALYSIS RESULTS

TABLE B-1

COMPOSITION OF VARIOUS FUEL OILS USED IN THE INTEGRATED FURNACE TESTING

	Rocketdyne Laboratory Oil	Pond Ave. Brookline, MA Unit #1	Richard Rd. Needham, MA Unit #4
Carbon, %	86.59	86.69	86.70
Hydrogen, %	13.20	12.87	12.92
Nitrogen, %	0.009	0.009	0.010
Sulfur, %	0.15	0.27	0.24
Gross Heat of Combustion, BTU/lb	19,467	19,992	19,990
API Gravity	36.3	36.2	36.0

TABLE B-2

TABULATION OF RESULTS OF FUEL OIL ANALYSES FOR FUEL-BOUND NITROGEN AND CARBON RESIDUE IN ORDER OF INCREASING CARBON RESIDUE

Oil Sample, Site-Month*	Fuel N_2, %	Flue No. g/kg	Carbon Residue %	Smoke, Bacharach	Est. of Heavy Bottoms, %	Color Density**
W-4	0.0200	.86	--	0.4	1/2	1
P-10	0.0090	.58	--	0.5	0	4
Lab	0.0085	.56	.07	0	0	6
G-1			.09	0	0	7
F-3			.13	0	0	1
R-3			.14	0	0	1
W-11			.15	0.7	1	7
P-3			.17	0.1	0	8
W-3			.17	0.2	1	3
W-2			.17	4.5	1	4
P-2			.20	0.5	0	1
R-2			.21	0	0	2
R-1			.23	0.5	0	3
R-11	0.0100	.51	.29	0.6	1/2	10
W-1			.56	2.5	5	10

*Sites:
W (Woodbine)
R (Richard)
P (Pond)
G (Gravon)
F (Fissette)
S (Stovepipe)

Months: 10/77 to 12/77
1/78 to 6/78

**Color Density - Arbitrary qualitative grading scale established on the existing field test oil sample stock grading the lightest (yellow) sample as 1 to the darkest (reddish brown) sample as 10.

TABLE B-3

OIL ANALYSES RESULTS OF THREE NO. 2 FUEL OIL SAMPLES TAKEN FROM DIFFERENT SOURCES

Fuel Oil Sample	Carbon Res. (10% Bottoms), %	Ash %	Kine. Viscosity @ 15°C Centistokes
Gravon (1/78)	0.09	0.004	4.35
Woodbine (1/78)	0.56	0.02	4.17
Laboratory	0.07	0.001	3.88
ASTM Maximum Specifications	0.35	-	3.60 (@ 38°C)

APPENDIX C

FIELD TEST MONTHLY MONITORING
DETAIL POLLUTANT EMISSIONS RESULTS

TABLE C-1

FLUE GAS EMISSIONS CONCENTRATION DATA OF THE BOSTON, MASSACHUSETTS, INTEGRATED FURNACE INSTALLATIONS AT THE START OF THE FIELD TEST PERIOD

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C
658	1.30	11.6	5.0	40	33	10	0.69	0.609	0.098	0.0	
659	1.30	11.5	5.0	40	34	10	0.69	0.629	0.099	0.0	
—Laboratory Fuel Oil—											
660	1.34	11.1	5.5	50	27	11	0.89	0.517	0.112	0.0	Unit #5 Woodbine St.
661	1.29	11.6	4.8	50	26	9	0.85	0.475	0.088	0.0	Newton, MA
662*	1.23	12.0	4.0	40	32	7	0.65	0.558	0.065	0.5	
—Steady State--											
663	1.23	12.1	4.0	25	33	2	0.41	0.575	0.019	1.5	
664	1.32	11.4	5.3	25	37	2	0.44	0.696	0.020	0.5	
665	1.27	11.7	4.6	20	38	2	0.34	0.687	0.019	0.5	
666	1.35	11.3	5.8	30	31	9	0.54	0.598	0.093	0.0	Unit #4 Needham, MA
667	1.23	12.0	4.1	30	39	7	0.49	0.684	0.065	0.3	
668*	1.23	12.0	4.1	25	40	7	0.41	0.701	0.065	0.3	
—Lab Fuel--											
669	1.29	11.3	4.7	35	34	7	0.60	0.622	0.068	0.3	
670	1.28	11.5	4.7	50	30	5	0.85	0.547	0.049	0.7	172
671	1.22	11.7	3.8	50	32	9	0.81	0.556	0.083	0.5	Unit #1
672	1.22	11.7	3.7	40	33	4	0.65	0.571	0.037	0.5	Pond Ave. 158
673*	1.22	11.7	3.7	20	36	7	0.32	0.623	0.065	0.5	Brookline,MA
--Lab Fuel--											
674	1.29	11.1	4.7	60	30	9	1.03	0.551	0.088	0.4	
675	1.28	11.1	4.6	80	29	12	1.36	0.530	0.117	0.5	

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*Burner operating set point

TABLE C-2

FLUE GAS EMISSIONS CONCENTRATION DATA OF THE ALBANY, NEW YORK, INTEGRATED FURNACE INSTALLATIONS AT THE START OF THE FIELD TEST PERIOD

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	
676	1.35	11.0	5.5	40	28	6	0.72	0.537	0.066	0.0	154	
677	1.27	11.5	4.5	30	32	6	0.51	0.578	0.058	0.0		Unit #2 Gravon Dr. Delmar, NY
678	1.22	12.0	3.9	25	34	3	0.41	0.590	0.028	0.0		
679*	1.23	11.9	3.9	25	36	2	0.41	0.627	0.023	0.0	159	
—Laboratory Fuel Oil--												
680	1.23	11.8	3.9	35	35	3	0.57	0.610	0.028	0.0		
681	1.22	11.9	3.8	30	36	2	0.49	0.625	0.019	0.0	143	
—Steady State--												
682	1.20	12.2	3.5	5	44	3	0.08	0.748	0.027	0.0	171	
—Steady State--												
683	1.22	12.7	4.0	50	32	8	0.81	0.552	0.074	0.0		Unit #3 Fissette Dr. Feura Bush, NY
684	1.25	12.2	4.5	157	30	10	2.62	0.534	0.095	0.0	126	
685*	1.22	12.7	4.0	139	32	7	2.24	0.552	0.064	0.0		
—Lab Fuel—												
686	1.23	12.6	4.1	120	29	5	1.95	0.505	0.046	0.0		
—Steady State—												
687	1.19	12.4	3.5	70	27	7	1.11	0.458	0.063	0.0		
688	1.21	12.4	3.7	70	26	2	1.12	0.446	0.018	0.0	137	
689	1.19	12.6	3.4	100	25	6	1.57	0.421	0.058	0.0	137	
690*	1.27	11.7	4.6	60	29	4	1.01	0.524	0.039	0.1		Unit #6 Stove Pipe Road Clarksville, NY
—Lab Fuel--												
691	1.29	11.5	4.9	70	33	22	1.20	0.607	0.221	0.1	134	

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*Burner operating set point

TABLE C-3

CYCLIC FLUE GAS POLLUTANT EMISSIONS CONCENTRATIONS FROM THE FIELD TEST UNITS OBTAINED ON THE FIRST MONTHLY MONITORING CHECK

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	
695	1.21	12.6	3.8	35	33	9	0.56	0.566	0.082	0.0	165	Unit #2 Gravon Rd. Delmar, NY
696	1.22	12.6	4.0	30	35	9	0.48	0.606	0.083	0.0	154	
697	1.33	11.7	5.6	167	22	11	2.96	0.417	0.111	0.0	146	Unit #6 Stovepipe Road Clarksville, NY
698	1.34	11.5	5.6	130	20	12	2.31	0.380	0.122	0.0	153	
699	1.26	12.0	4.5	130	18	7	2.17	0.322	0.067	0.1	152	
700	1.23	12.2	4.0	130	18	10	2.11	0.313	0.093	0.0	150	
701	1.21	12.4	3.8	139	18	12	2.23	0.309	0.110	0.0		
702	1.18	12.9	3.4	80	29	60	1.25	0.486	0.536	0.0		Unit #3 Fissette Dr. Feura Bush, NY
703	1.19	12.7	3.6	80	31		1.27	0.525		0.0		
704	1.21	12.6	3.9	85	31	40	1.37	0.534	0.367	0.0	152	
705	1.16	12.7	3.0	1275	22	100	19.53	0.361	0.875	2.5		Unit #5 Woodbine St. Newton, MA
706	1.15	12.9	2.9	≥1600	24	130	≥24.30	0.391	1.128	3.0		
707	1.32	11.5	5.4	20	41	5	0.35	0.773	0.050			
708	1.23	12.2	4.0	23	39	3	0.39	0.679	0.028	0.7		
709	1.23	12.2	4.0	23	39	3	0.39	0.679	0.028	0.7		
710	1.22	12.6	4.0	342	21	6	5.52	0.363	0.055	0.4		Unit #4 Richard Road Needham, MA
711	1.22	12.6	4.0	355	20	5	5.75	0.346	0.046	0.5		
712	1.24	12.6	4.3	100	29	2	1.64	0.509	0.019	0.8		
713	1.30	12.0	5.2	45	30	7	0.78	0.554	0.069	2.0	174	Unit #1 Pond Ave. Brookline, MA
714	1.30	12.0	5.2	45	32	7	0.78	0.591	0.069	2.0		

TABLE C-4

CYCLE-AVERAGED FLUE GAS ANALYSIS DATA OBTAINED ON THE SECOND MONTHLY FIELD CHECK

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C		
715	1.49	10.2	7.3	90	32	9	1.79	0.683	0.102	2.0	143		Woodbine St. Newton, MA Unit #5
716	1.48	10.2	7.2	100	31	9	1.98	0.658	0.102	2.0			
717	1.21	12.7	3.8	45	28	3	0.72	0.479	0.027	0.6	135		
718	1.21	12.7	3.9	40	30	2	0.64	0.516	0.023	0.8			
719	1.21	12.7	3.9	50	29	3	0.80	0.498	0.027				
720	1.26	12.0	4.5	167	22	5	2.80	0.393	0.048				Richard Rd. Needham, MA Unit #4
721	1.26	11.9	4.5	187	23	5	3.14	0.412	0.048	0.5			
722	1.26	11.9	4.5	177	25	5	2.97	0.447	0.048	0.3			
723	1.37	11.3	6.0	41	23	7	0.76	0.449	0.073	2.2	169	0.75-80°-A	Pond Ave. Brookline, MA Unit #1
724	1.37	11.3	6.1	40	24	7	0.73	0.469	0.078	2.3			
725	1.21	12.9	4.0	35	30	6	0.56	0.517	0.055	0.0			
726	1.21	13.0	3.9	35	31	5	0.56	0.532	0.050	0.0	169		
727	1.21	12.8	3.9	36	31	4	0.59	0.532	0.041	0.0			
728	1.30	11.6	5.0	70	23	5	1.21	0.424	0.054	0.3			Stovepipe Rd. Clarksville, NY Unit #6
729	1.31	11.4	5.1	61	23	4	1.08	0.428	0.040	0.5			
730	1.31	11.3	5.1	70	22	3	1.22	0.410	0.035		146		
731	1.20	12.7	3.7	45	28	9	0.72	0.477	0.082	0.0			Fissette Dr. Feura Bush, NY Unit #3
732	1.20	12.9	3.7	51	29	7	0.82	0.493	0.063	0.0			
733	1.20	12.9	3.7	58	29	7	0.94	0.493	0.063		132		
734	1.24	12.6	4.4	35	27	5	0.58	0.477	0.049	0.0			Gravon Rd. Delmar, NY Unit #2
735	1.24	12.6	4.4	35	28	4	0.58	0.494	0.042	0.0	152		
736	1.24	12.6	4.4	30	28	4	0.49	0.494	0.042		153		

TABLE C-5

FLUE GAS POLLUTANT EMISSIONS MEASUREMENTS OBTAINED ON THE THIRD MONTHLY CHECK OF THE FIELD TEST INTEGRATED FURNACE SYSTEMS

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	
737	1.18	12.7	3.4	31	30	4	0.50	0.504	0.036	0.0	136	Fiasette Dr. Feura Bush, NY Unit 3
738	1.18	12.7	3.4	31	31	4	0.50	0.521	0.036	0.1		
739	1.18	12.7	3.4	35	31	4	0.55	0.521	0.036	0.0	140	
740	1.31	11.9	5.4	30	30	6	0.52	0.561	0.060	0.0	162	Gravon Rd. Delmar, NY Unit 5
741	1.30	11.9	5.2	30	30	6	0.52	0.556	0.059	0.0		
742	1.31	11.8	5.3	30	28	5	0.52	0.522	0.050	0.0	159	
743	1.27	12.4	4.9	60	24	4	1.01	0.434	0.043	1.3	160	Stovepipe Rd. Clarksville, NY Unit 6
744	1.27	12.5	4.9	50	24	3	0.84	0.434	0.034	1.3		
745	1.27	12.3	4.9	30	29	2	0.51	0.526	0.019	0.1		
746	1.23	12.7	4.2	30	31	2	0.49	0.540	0.019	0.0	168	
747	1.19	12.9	3.6	41	29	2	0.66	0.490	0.018	2.5	169	Pond Ave. Brookline, Ma Unit 1
748	1.19	12.9	3.6	41	28	2	0.66	0.474	0.018	2.5		
749	1.20	13.1	3.8	40	33	2	0.64	0.562	0.023	0.0		
750	1.19	13.3	3.6	30	34	2	0.47	0.573	0.018	0.0		
751	1.49	10.6	7.5	167	22	25	3.33	0.468	0.284	0.0		Richard Rd. Needham, MA Unit 4
752	1.37	11.3	6.1	139	27	6	2.54	0.528	0.063	0.0		
753	1.29	12.1	5.1	40	27	3	0.69	0.495	0.034	0.0		
754	1.27	12.4	4.8	45	28	4	0.76	0.504	0.038	0.5		
755	1.27	12.4	4.9	40	28	2	0.68	0.507	0.019	0.5		
756	1.28	12.3	5.0	50	32	4	0.85	0.583	0.044	3.5		Woodbine St. Newton, MA Unit 5
757	1.24	12.5	4.4	30	32	4	0.49	0.565	0.038	2.5		
758	1.27	12.2	4.7	30	34	5	0.50	0.612	0.048	2.5		
759	1.31	11.9	5.3	31	35	9	0.56	0.652	0.089	3.0		
760	1.23	12.6	4.1	30	34	5	0.49	0.591	0.046	2.5		
761	1.22	12.6	4.0	30	34	7	0.49	0.589	0.065	2.5		
762	1.22	12.6	4.0	25	34	9	0.40	0.589	0.083	2.5	167	

TABLE C-6

FLUE GAS POLLUTANT EMISSIONS MEASUREMENTS OBTAINED ON THE FOURTH MONTHLY CHECK OF THE FIELD TEST INTEGRATED FURNACE SYSTEMS

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	
763	1.23	12.5	4.1	30	33	4	0.49	0.574	0.037	0.6	169	Pond Ave. Brookline, MA Unit #1
764	1.24	12.4	4.4	30	32	4	0.50	0.566	0.038	0.5	-	
765	1.24	12.2	4.3	25	34	4	0.41	0.600	0.038	0.5	-	
766	1.37	11.9	6.3	35	24	4	0.64	0.468	0.042	4.0	-	Woodbine St. Newton, MA Unit #5
767	1.34	12.2	6.8	45	26	4	0.80	0.496	0.041	4.0	-	
768	1.42	11.0	6.6	30	24	3	0.57	0.485	0.032	0.0	-	
769	1.54	10.2	8.0	35	22	3	0.72	0.485	0.035	0.0	-	
770	1.49	11.0	7.8	25	22	3	0.52	0.469	0.034	0.0	147	Richard Rd. Needham, MA Unit #4
771	1.24	12.9	4.6	1499	18	100	24.63	0.317	0.930	1.3	-	
772	1.37	11.7	6.3	139	18	6	2.54	0.352	0.063	0.0	-	
773	1.43	11.0	6.8	25	25	4	0.48	0.510	0.044	0.0	-	
774	1.45	10.8	7.0	27	25	3	0.54	0.517	0.033	0.0	-	
775	1.12	14.1	2.5	139	30	12	2.06	0.477	0.102	5.5	-	
776	1.27	12.4	4.9	25	32	7	0.42	0.579	0.060	3.5	-	-Recheck-
777	1.25	12.7	4.6	30	30	6	0.50	0.532	0.057	4.5	-	Woodbine St. Newton, MA Unit #5
778	1.26	12.6	4.8	40	30	7	0.67	0.539	0.067	4.5	-	
779	1.27	12.4	4.9	35	32	7	0.59	0.579	0.072	4.5	173	
780	1.29	12.2	5.1	30	29	5	0.51	0.531	0.047	1.0	-	
781	1.33	11.9	5.6	31	28	8	0.56	0.529	0.081	1.0	-	
782	1.30	12.0	5.3	31	27	8	0.55	0.501	0.079	1.0	-	
783	1.23	12.6	4.2	35	27	6	0.57	0.472	0.056	1.0	-	
784	1.33	11.3	5.4	40	31	4	0.71	0.587	0.040	1.0	-	Cravon Dr. Delmar, NY Unit #2
785	1.33	11.3	5.4	30	31	4	0.53	0.587	0.040	1.0	-	
786	1.31	11.5	5.2	30	31	5	0.52	0.579	0.050	1.0	-	
787	1.31	11.5	5.2	30	31	4	0.52	0.579	0.040	1.0	-	
788	1.24	12.6	4.3	50	29	4	0.82	0.509	0.037	1.0	-	
789	1.28	12.4	5.0	40	29	4	0.68	0.527	0.039	1.0	181	
790	1.20	13.0	3.8	35	28	3	0.56	0.477	0.027	0.0	-	Stovepipe Rd. Clarkeville, NY Unit #6
791	1.20	13.0	3.7	30	28	3	0.48	0.475	0.027	0.1	176	
792	1.20	12.8	3.8	47	33	5	0.77	0.564	0.046	0.0	-	Fiamette Dr. Feura Bush, NY Unit #3
793	1.19	12.9	3.6	45	35	5	0.73	0.592	0.045	0.0	-	
794	1.19	12.8	3.5	50	35	6	0.79	0.590	0.050	0.0	148	

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TABLE C-7

FLUE GAS POLLUTANT EMISSIONS MEASUREMENTS OBTAINED ON THE FIFTH MONTHLY CHECK OF THE FIELD TEST INTEGRATED FURNACE SYSTEMS

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	
795	1.23	12.9	4.3	40	28	5	0.65	0.489	0.047	0.0	-	Fissette Feura Bush, NY Unit #3
796	1.25	12.7	4.6	40	28	4	0.66	0.497	0.038	0.0	149	
797	1.25	12.2	4.5	37	30	6	0.63	0.535	0.057	0.0	149	Gravon Delmar, NY Unit #2
798	1.25	12.2	4.5	37	29	6	0.63	0.516	0.057	0.0	148	
799	1.26	12.2	4.6	25	30	6	0.42	0.537	0.057	0.0	-	
800	1.24	12.4	4.3	40	34	5	0.66	0.598	0.047	0.0	159	Stovepipe Clarksville, NY Unit #6
801	1.23	12.4	4.1	40	36	5	0.65	0.628	0.046	0.0	163	
802	1.31	11.7	5.3	30	32	4	0.52	0.598	0.040	0.5	-	Pond Brookline, MA Unit #1
803	1.31	11.9	5.3	25	33	4	0.43	0.614	0.040	0.0	-	
804	1.31	11.9	5.3	25	30	5	0.43	0.559	0.050	0.0	186	
805	1.24	12.6	4.4	45	26	4	0.74	0.458	0.042	0.0	-	Richard Needham, MA Unit #4
806	1.24	12.6	4.4	40	27	3	0.66	0.476	0.028	0.0	-	
807	1.24	12.6	4.4	40	27	4	0.66	0.476	0.038	0.0	156	
808	1.31	11.9	5.4	50	45	10	0.87	0.842	0.100	0.4	-	Woodbine Newton, MA Unit #5
809	1.32	11.7	5.5	50	45	8	0.88	0.849	0.080	0.0	178	
810	1.28	11.9	4.9	50	46	9	0.85	0.841	0.088	HT.X.ENTR.		
811	1.24	12.2	4.2	139	46	7	2.28	0.808	0.066	OVER FIRE		

TABLE C-8

FLUE GAS AND COMBUSTION GAS POLLUTANT EMISSIONS MEASUREMENTS OBTAINED ON THE SIXTH MONTHLY CHECK OF THE FIELD TEST INTEGRATED FURNACE SYSTEMS

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TEC C	
812	1.36	11.4	5.9	45	45	10	0.81	0.870	0.103	-	192	WOODBINE STREET, UNIT 5
813	1.36	11.4	5.9	47	46	10	0.87	0.889	0.103	0.5	-	
814	1.36	11.4	5.9	50	45	10	0.92	0.870	0.103	0.2	-	
815	1.22	12.6	4.1	456	47	36	7.40	0.816	0.333	FB	-	
816	1.22	12.6	4.0	456	46	36	7.38	0.797	0.333			
817	1.34	11.5	5.6	55	46	10	0.99	0.877	0.102	HX		
818	1.33	11.5	5.5	60	45	10	1.06	0.852	0.101			
819	1.27	12.4	4.9	41	28	5	0.71	0.507	0.048	0.0	142	RICHARD ROAD, UNIT 4
820	1.29	12.0	4.9	40	27	5	0.68	0.492	0.047	0.0	144	
821	1.14	13.1	2.8	910	36	45	13.78	0.584	0.389	FB		
822	1.14	13.1	2.7	808	38	45	12.18	0.613	0.387			
823	1.17	13.3	3.2	50	36	9	0.77	0.597	0.080	HX		
824	1.17	13.3	3.2	50	37	10	0.77	0.612	0.088			
825	1.26	12.9	4.9	41	31	6	0.70	0.556	0.057	-	-	
826	1.17	13.3	3.3	50	33	10	0.78	0.549	0.089	OUT. MANIF.		
827	1.19	13.3	3.7	40	35	7	0.63	0.592	0.063	0.0	-	FLUE (TAPED ALL JOINTS)
828	1.19	13.2	3.6	46	34	7	0.74	0.573	0.063	0.1	-	
829	1.19	13.1	3.6	50	35	6	0.79	0.591	0.054	-	142	
830	1.19	12.9	3.6	40	36	5	0.63	0.609	0.042	0.0	170	POND AVE., UNIT 1
831	1.17	13.2	3.2	36	36	4	0.57	0.596	0.035	0.0	169	
832	1.18	12.9	3.5	1339	36	110	20.95	0.603	0.983	FB		
833	1.17	13.1	3.3	45	37	4	0.70	0.616	0.036	HX		
834	1.29	12.0	5.1	50	31	4	0.86	0.570	0.039	0.0	166	GRAYON ROAD, UNIT 2
835	1.29	12.0	5.1	40	33	3	0.69	0.607	0.034	0.1	167	
836	1.28	12.0	4.9	519	33	20	8.81	0.600	0.194	FB		
837	1.28	12.1	4.9	45	35	3	0.76	0.636	0.029	HX		
838	1.29	12.0	5.0	40	34	3	0.68	0.622	0.029	0.0	-	
839	1.21	13.1	3.9	45	34	3	0.72	0.581	0.027	-	159	STOVE-PIPE ROAD, UNIT 6
840	1.21	12.9	3.9	45	34	3	0.72	0.583	0.027	0.0	158	
841	1.21	12.7	3.9	45	34	2	0.72	0.594	0.018	0.0	-	
842	1.18	13.1	3.5	-1600	32	150	-24.95	0.535	1.336	FB		
843	1.21	13.1	3.9	50	34	3	0.80	0.581	0.027	HX		
844	1.20	12.8	3.8	45	31	5	0.72	0.530	0.050	0.0	167	BISSETTE DRIVE, UNIT 3
845	1.20	12.9	3.8	50	31	5	0.80	0.529	0.050	0.0	166	
846	1.20	12.7	3.9	1499	30	70	23.93	0.513	0.638	FB		
847	1.21	12.9	3.9	47	32	5	0.77	0.549	0.050	HX		

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TABLE C-9

FLUE GAS AND COMBUSTION GAS POLLUTANT EMISSIONS MEASUREMENTS OBTAINED ON THE SEVENTH MONTHLY CHECK OF THE FIELD TEST INTEGRATED FURNACE SYSTEMS

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	
	1.20						<1.00	<0.650	<0.100	<1.0		DESIGN GOALS
848	1.20	12.9	3.8	56	29	5	0.91	0.495	0.046	0.1	147	FISSETTE UNIT NO. 3
849	1.19	12.9	3.5	57	29	5	0.91	0.488	0.045	0.2	-	
850	1.19	12.9	3.5	56	28	5	0.90	0.471	0.045	0.1	-	
851	1.21	13.1	3.9	40	32	2	0.64	0.547	0.018	0.0	-	STOVEPIPE UNIT NO. 6
852	1.20	13.0	3.8	50	31	2	0.80	0.528	0.018	0.0	-	
853	1.21	13.1	3.9	50	31	2	0.80	0.530	0.018	-	-	
854	1.27	12.2	4.8	40	35	3	0.67	0.632	0.029	0.0	-	GRAVON UNIT NO. 2
855	1.27	12.2	4.8	40	36	4	0.67	0.650	0.039	0.0	-	
856	1.25	12.4	4.5	37	38	4	0.63	0.675	0.038	-	152	
857	1.27	12.2	4.8	37	38	4	0.64	0.687	0.039	-	151	
858	1.23	12.6	4.3	31	36	2	0.52	0.631	0.019	0.1	164	POND UNIT NO. 1
859	1.24	12.7	4.4	40	36	2	0.66	0.633	0.019	0.0	164	
860	1.24	12.6	4.5	1259	38	55	20.73	0.670	0.517	FB		
861	1.23	12.7	4.2	50	35	3	0.81	0.610	0.028	-	153	RICHARD UNIT NO. 4
862	1.23	12.8	4.2	50	35	3	0.81	0.609	0.028	0.0	-	
863	1.22	12.9	4.1	50	36	3	0.81	0.623	0.028	0.0	-	
864	1.19	13.2	3.7	1019	38	50	16.05	0.641	0.450	FB		
865	1.33	12.2	5.8	47	51	6	0.85	0.964	0.060	0.0	174	WOODFINE UNIT NO. 5
866	1.32	12.2	5.7	50	50	8	0.88	0.941	0.080	0.0	174	
867	1.22	12.8	4.1	1179	52	80	18.99	0.897	0.736	FB		
868	1.27	12.6	4.9	50	52	6	0.84	0.938	0.058	HX		

TABLE C-10

FLUE GAS AND COMBUSTION GAS POLLUTANT EMISSIONS MEASUREMENTS OBTAINED ON THE FINAL CHECK OF THE FIELD TEST INTEGRATED FURNACE SYSTEMS IN THE 1977-1978 HEATING SEASON

RUN NO.	STOIC. RATIO	CO2 %	O2 %	CO PPM	NO PPM	UHC PPM	CO GM/KGM	NO GM/KGM	UHC GM/KGM	BACH. SMOKE	NET TFG C	
	1.20						<1.00	<0.650	<0.100	<1.0		DESIGN GOALS
869	1.19	12.9	3.5	37	36	2	0.60	0.606	0.018	0.0	140	POND
870	1.19	12.9	3.5	37	36	2	0.60	0.606	0.018	0.0	140	UNIT NO. 1
871	1.19	12.7	3.6	1419	30	70	22.40	0.507	0.631	FB		
872	1.31	11.9	5.4	40	33	6	0.70	0.617	0.060	0.5	163	WOODBINE
873	1.32	11.7	5.5	55	33	7	0.97	0.622	0.070	0.9	163	UNIT NO. 5
874	1.24	12.4	4.4	889	37	60	14.67	0.654	0.565	FB		
875	1.30	11.9	5.1	41	35	6	0.72	0.646	0.059	HX		
876	1.22	12.8	4.0	50	37	5	0.81	0.638	0.046	0.0	135	RICHARD
877	1.23	12.7	4.2	47	37	4	0.78	0.645	0.037	0.0	137	UNIT NO. 4
878	1.21	12.8	3.9	1019	37	32	16.27	0.633	0.292	FB		
879	1.21	12.8	3.9	80	38	6	1.28	0.652	0.055	HX		
880	1.22	12.7	4.0	51	38	5	0.84	0.658	0.046	0.0	138	
881	1.25	12.7	4.6	37	38	4	0.63	0.674	0.038	0.1	-	GRAVON
882	1.24	12.8	4.4	35	39	4	0.57	0.685	0.037	0.0	-	UNIT NO. 2
883	1.23	12.8	4.3	30	38	4	0.49	0.664	0.037	0.0	-	
884	1.24	12.8	4.5	27	39	4	0.46	0.689	0.038	-	147	
885	1.24	12.8	4.4	30	38	4	0.49	0.667	0.037	-	147	
886	1.18	13.3	3.5	90	37	7	1.41	0.620	0.063	-	131	FISSETTE
887	1.18	13.3	3.5	90	39	7	1.41	0.654	0.063	-	134	UNIT NO. 3
888	1.20	13.1	3.8	90	38	7	1.43	0.647	0.064	0.0	-	
889	1.19	13.1	3.7	100	37	6	1.58	0.627	0.054	0.0	-	
890	1.18	13.2	3.5	80	38	2	1.25	0.638	0.018	0.0	-	STOVEPIPE
891	1.18	13.2	3.5	70	38	2	1.10	0.638	0.018	0.0	161	UNIT NO. 6
892	1.18	13.3	3.4	90	38	2	1.40	0.634	0.018	-	160	

APPENDIX D

FIELD TEST CYCLE-AVERAGED GROSS THERMAL EFFICIENCY DATA

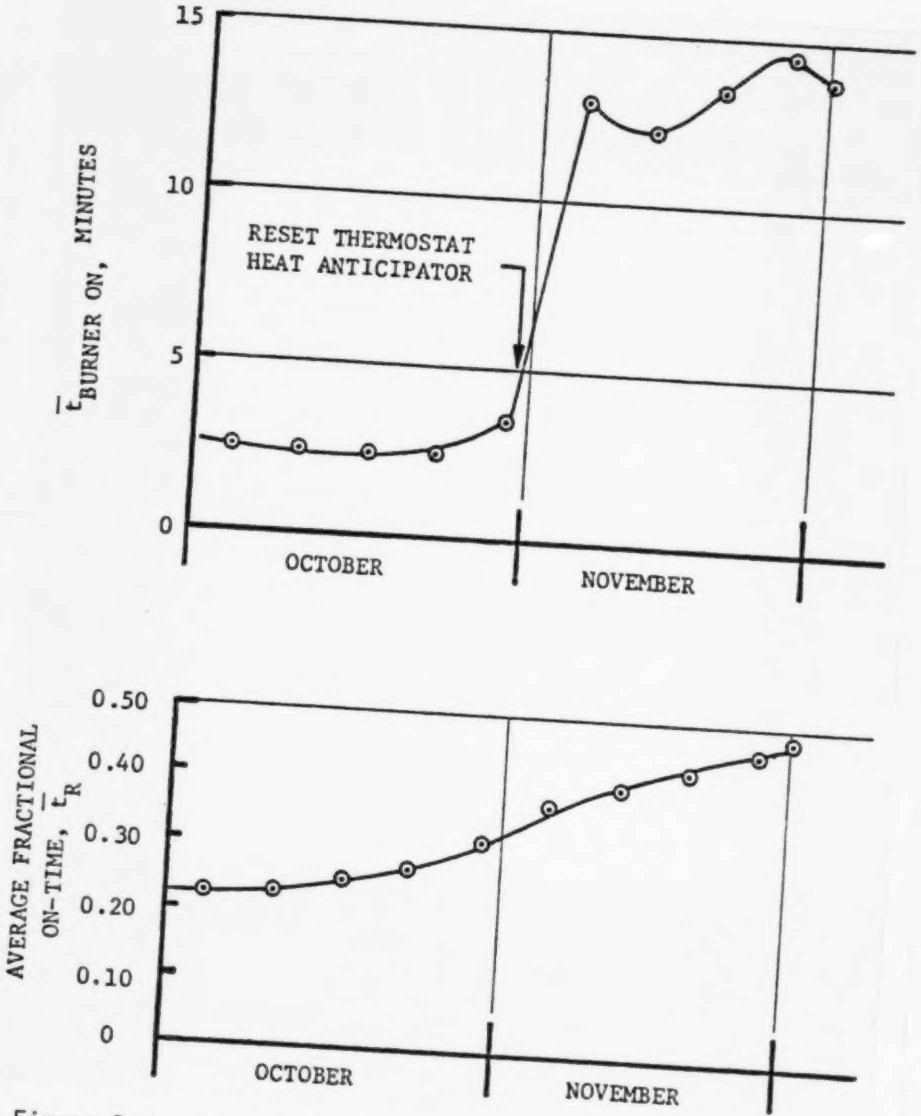


Figure D-1. Average Operating Cycle Timing Characteristics of Unit No. 5 Measureed by the Hewlett/Packard Automatic Data Logging System

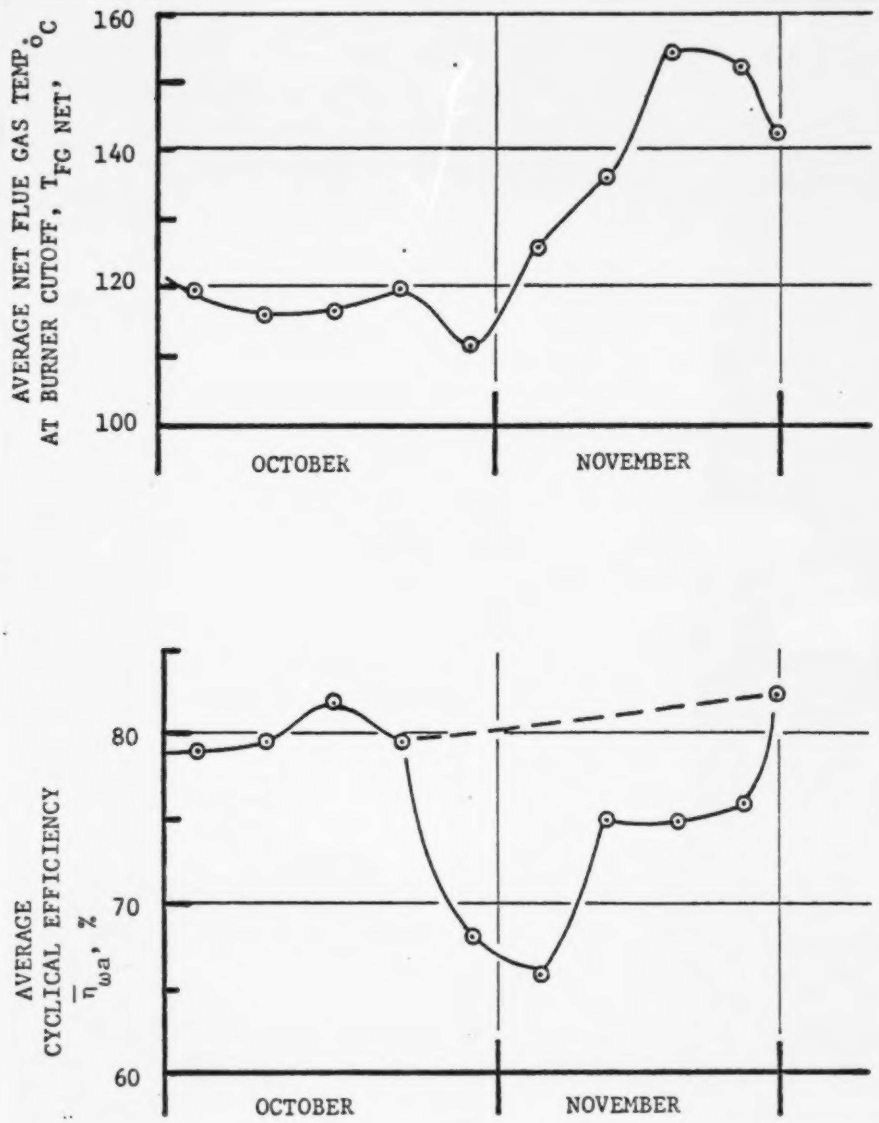


Figure D-2. Average Operating Cycle Flue Gas Temperature and Gross Warm-Air Efficiency Measured on Unit No. 5 by the H/P Automatic Data Logging System

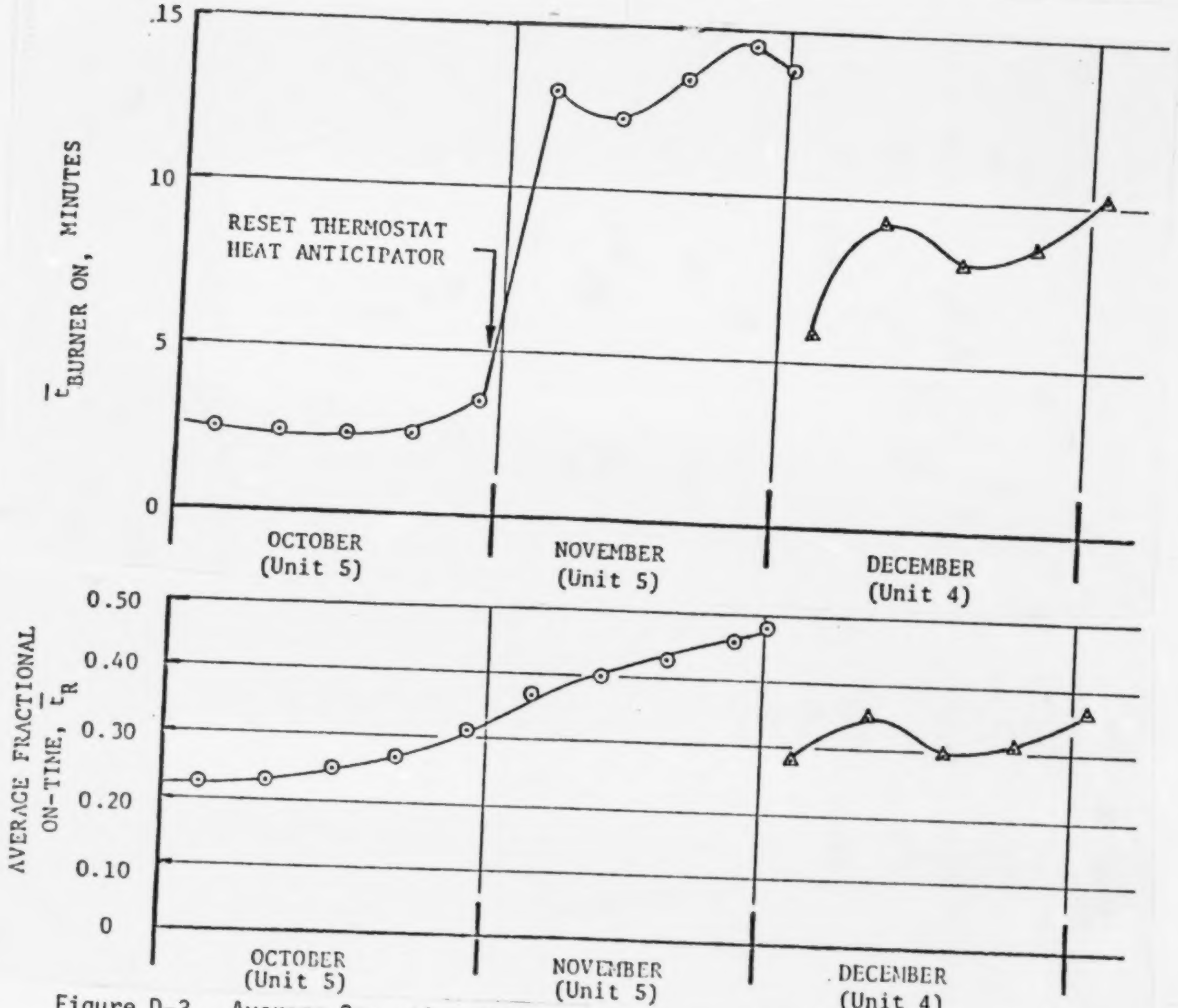


Figure D-3. Average Operating Cycle Timing Characteristics of Units 5 and 4 Measured by the H/P Automatic Data Logging System

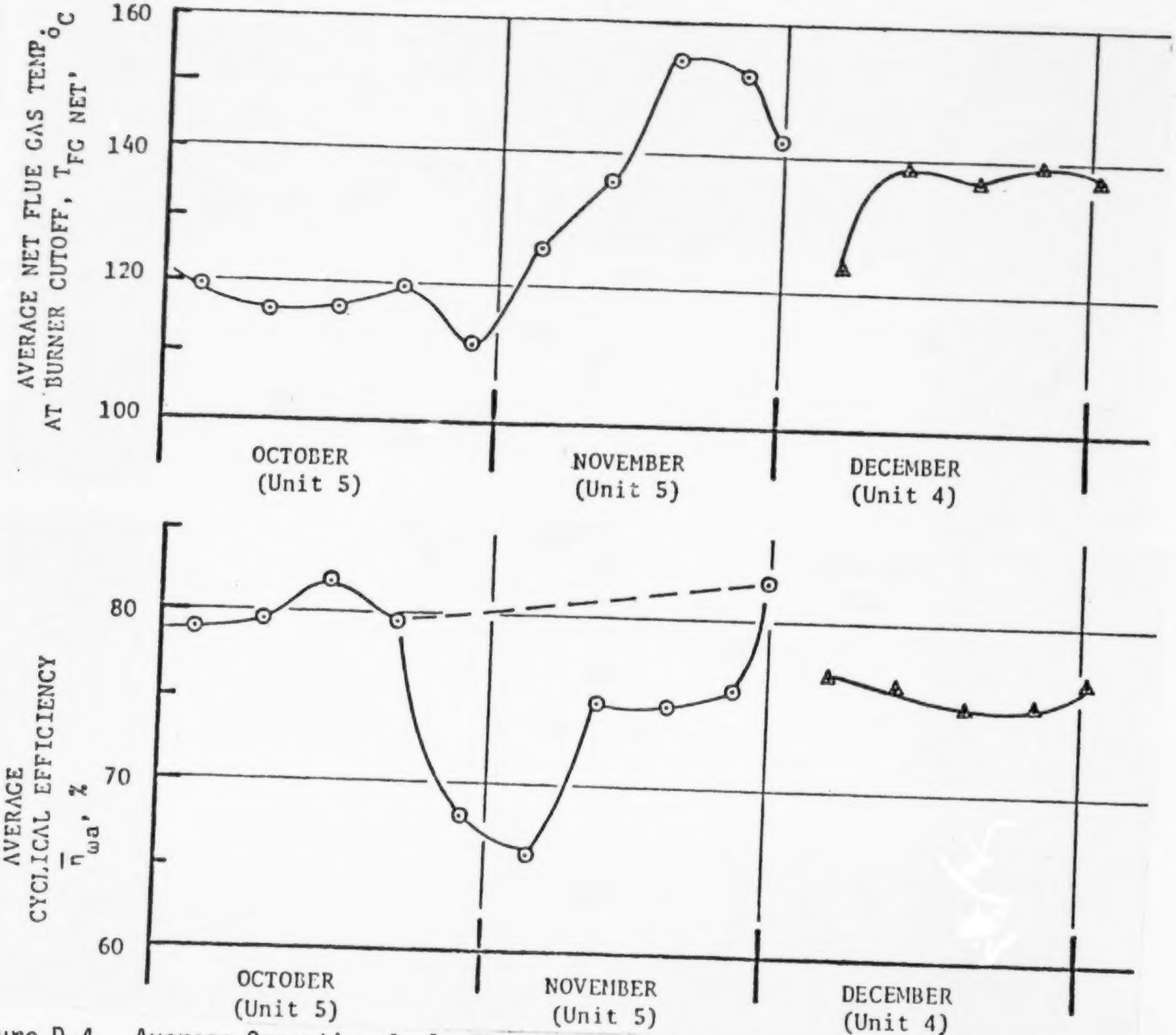


Figure D-4. Average Operating Cycle Flue Gas Temperature and Gross Warm-Air Efficiency Measured on Units 5 and 4 by the H/P Automatic Data Logging System

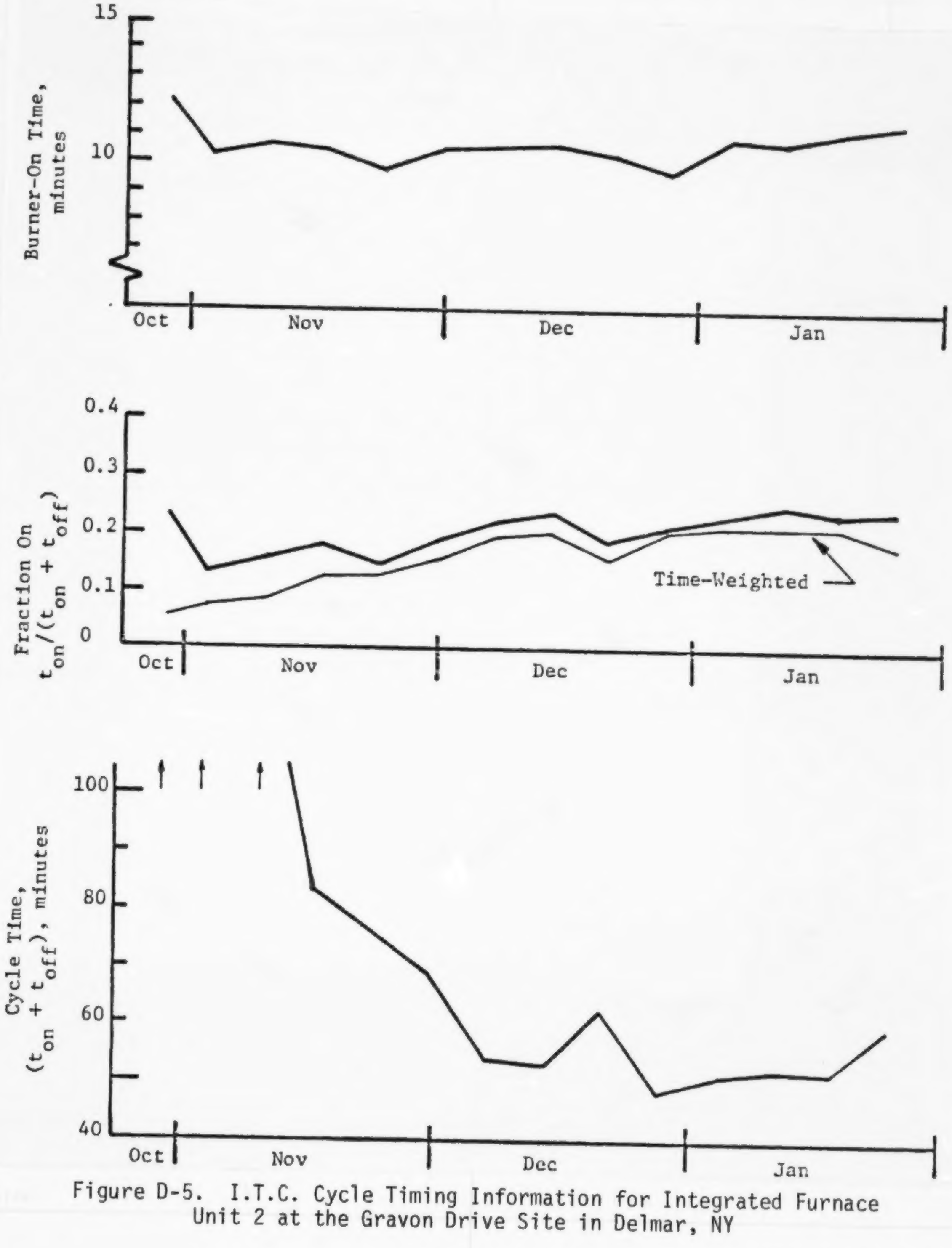


Figure D-5. I.T.C. Cycle Timing Information for Integrated Furnace Unit 2 at the Gravon Drive Site in Delmar, NY

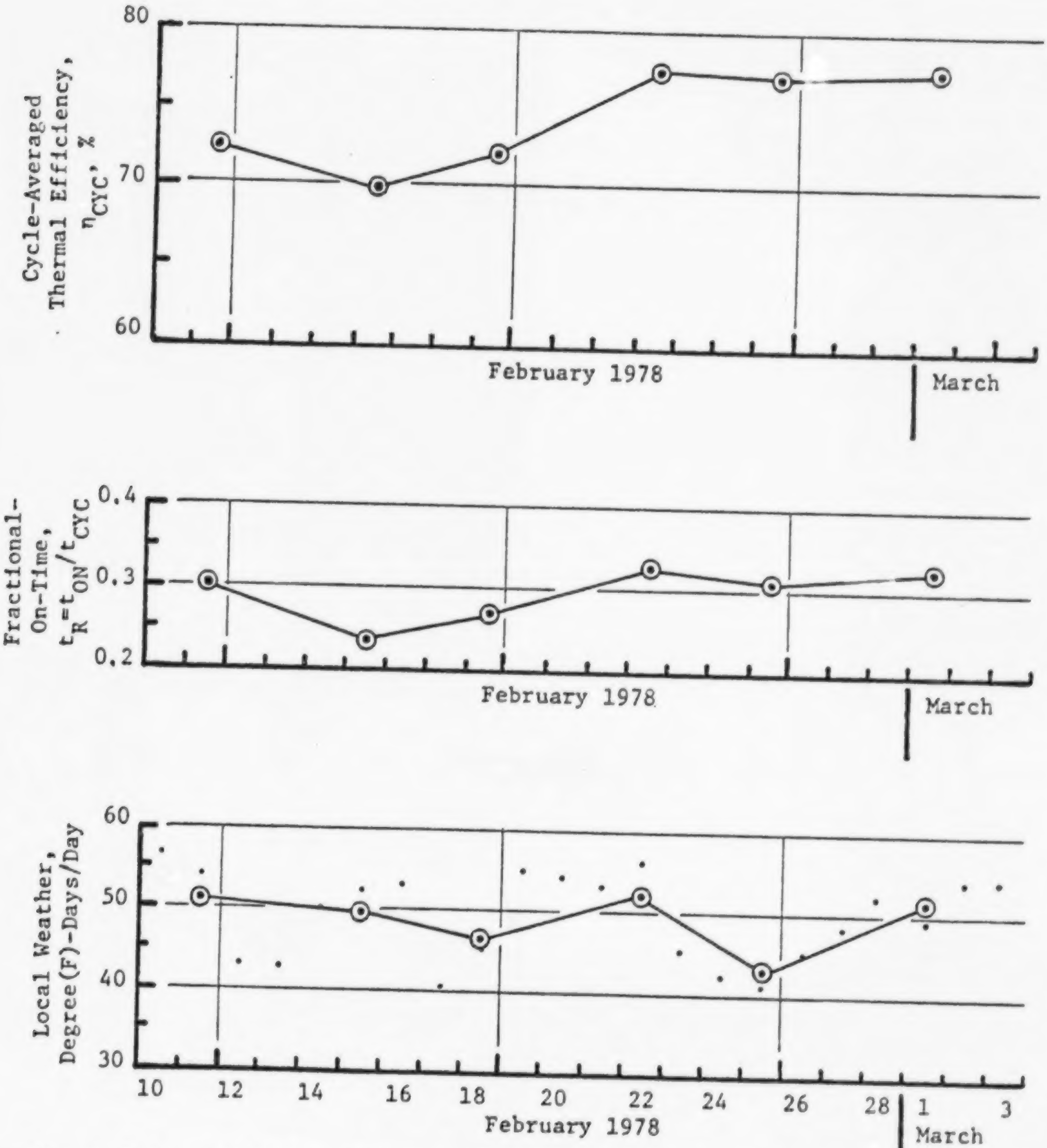


Figure D-6. Cycle-Averaged Thermal Efficiency Information for Integrated Furnace Unit 2 at the Gravon Road Site in Delmar, NY

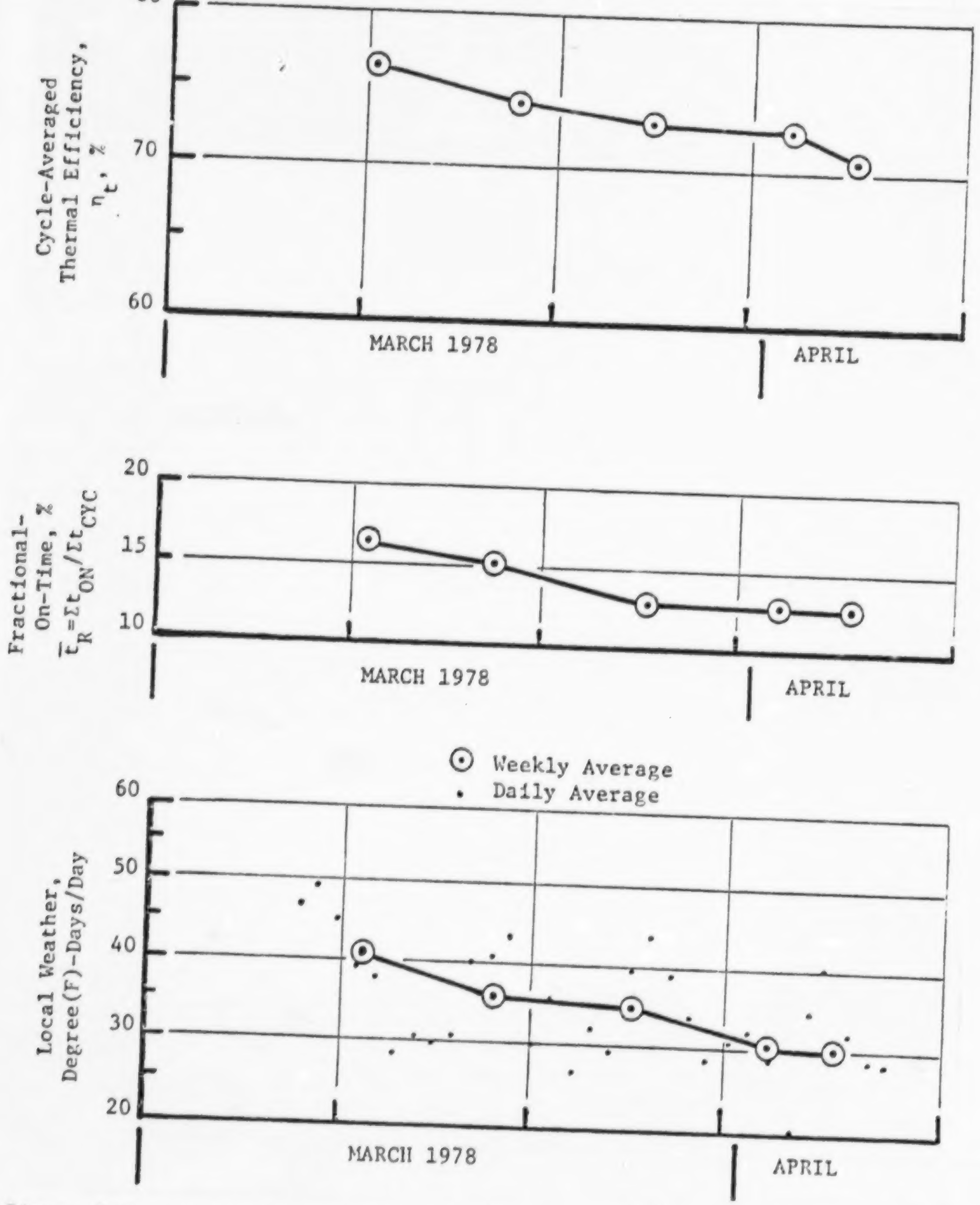


Figure D-7. Cycle-Averaged Thermal Efficiency Information for Integrated Furnace Unit 6 at the Stovepipe Road Site in Clarksville, NY

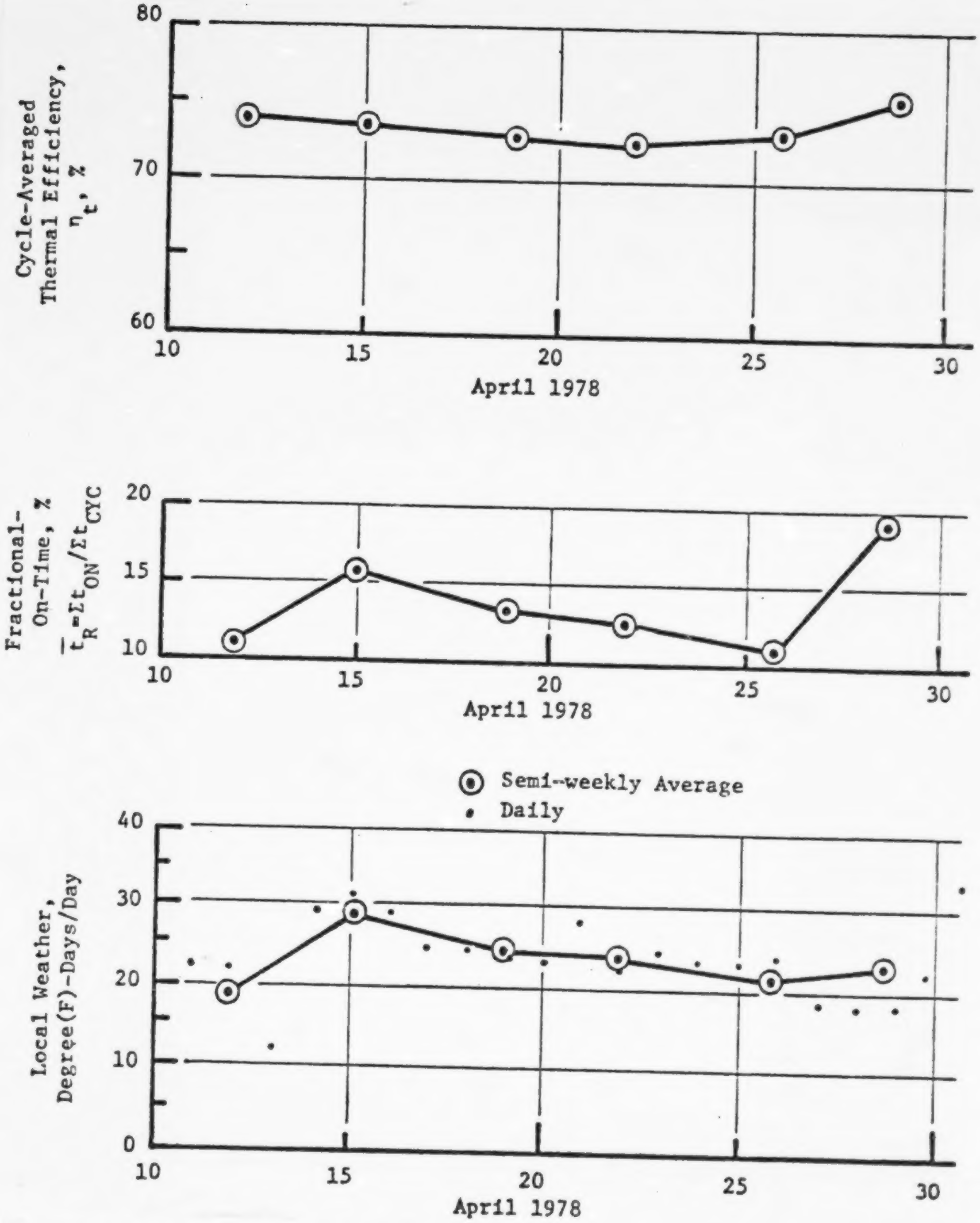


Figure D-8. Cycle-Averaged Thermal Efficiency Information for Integrated Furnace Unit 3 at the Fissette Drive Site in Feura Bush, NY

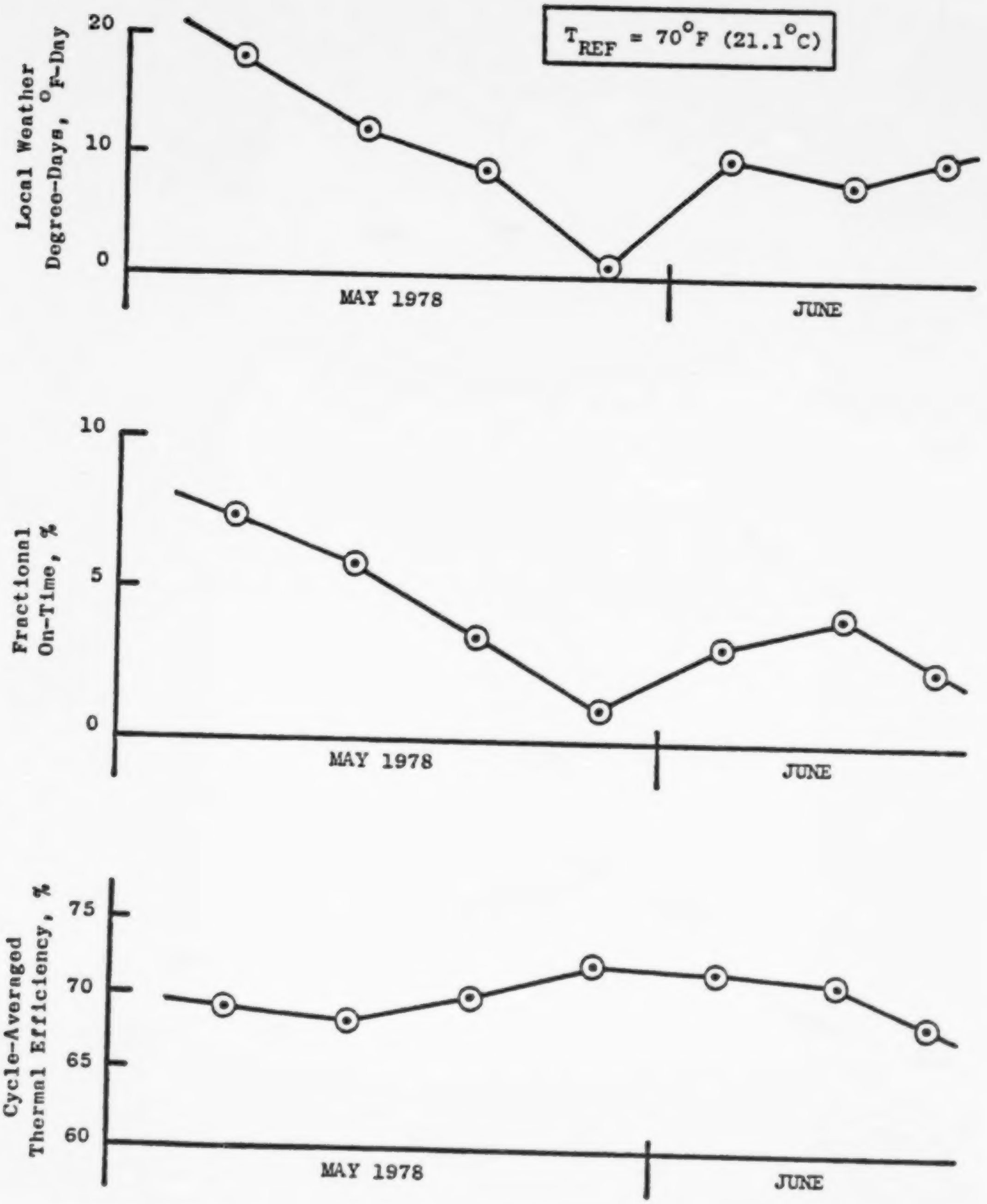
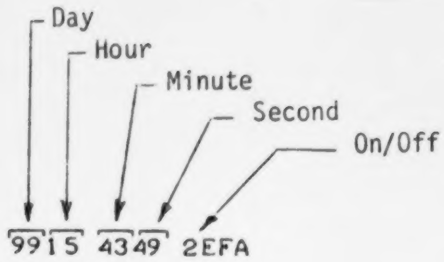


Figure D-9. Weekly-Averaged Integrated Furnace No. 3 Performance Data Acquired at the Fissette Drive Test Site During May-June 1978



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9915 5131 5EFA
9916 2430 2EFA
9916 3215 5EFA
9917 0408 2EFA
9917 1227 5EFA
9917 4136 2EFA
9917 5550 5EFA
9918 1453 2EFA
9918 2511 5EFA
9918 4608 2EFA
9918 5501 5EFA
9919 1843 2EFA
9919 2646 5EFA
9920 1914 2EFA
9920 2644 5EFA
9920 5900 2EFA
9921 0706 5EFA
9921 4217 2EFA
9921 5018 5B9A
```

Figure D-10. Tabulation of a Segment of Cycle Time Data Recorded by the I.T.C. 9676 Data Logger

TABLE D-11

COMPARISON OF AVERAGE OPERATIONAL THERMAL EFFICIENCY USING TWO DIFFERENT COMPUTATIONAL TECHNIQUES

Furnace Test Site	$\overline{\eta}_N$ Firing-Weighted %	$\overline{\eta}_t$ t_{on}-Weighted %	Diff. %
Stovepipe	102.6	73.5	-28.4
Gravon	74.0	70.5	-4.7
Pond	73.4	73.0	-0.4
Richard	75.5	77.1	+2.1
Woodbine	80.9	80.6	-0.3

where:

$$\overline{\eta}_N = \frac{100 \cdot \Sigma \eta}{N}$$

$$\overline{\eta}_t = \frac{100 \cdot \Sigma\ t_{on} \cdot \eta}{\Sigma\ t_{on}} = \frac{\frac{100}{\dot{w}_{oil} \cdot h_c} \cdot \Sigma\ Q_{out}}{\Sigma\ t_{on}} = \frac{100 \cdot \Sigma\ Q_{out}}{\Sigma\ Q_{in}}$$

TABLE D-12

TABULATION OF TIME-BASED FURNACE USAGE DATA FROM THE I.T.C. DATA LOGGER INSTALLED ON INTEGRATED FURNACE UNIT 2 AT THE GRAVON DRIVE SITE

18 December 1978, Sunday

Day	Time	t_{on}	t_{cyc}	t_R
52	0:27	9.75	46.45	0.2099
52	1:13	9.35	43.53	0.2148
52	1:57	9.67	43.83	0.2205
52	2:41	7.67	53.52	0.1433
52	3:31	9.37	46.27	0.2024
52	4:20	9.62	45.70	0.2104
52	5: 6	9.55	45.52	0.2098
52	5:52	9.77	45.35	0.2154
52	6:37	9.73	44.97	0.2165
52	7:22	9.50	48.57	0.1956
52	8:10	9.93	46.93	0.2116
52	8:57	9.93	46.73	0.2126
52	9:44	24.32	49.38	0.4924
52	10:33	11.18	38.52	0.2904
52	11:12	10.78	40.12	0.2688
52	11:52	9.85	41.25	0.2388
52	12:33	10.05	43.07	0.2334
52	13:16	9.90	40.35	0.2454
52	13:57	16.88	137.22	0.1230
52	16:14	9.57	54.92	0.1742
52	17: 9	9.38	51.87	0.1809
52	18: 1	9.47	51.30	0.1845
52	18:52	9.50	12.98	0.7317
52	19: 5	15.00	39.45	0.3802
52	19:44	10.72	39.15	0.2737
52	20:24	9.95	58.97	0.1687
52	21:23	9.17	150.28	0.0610

19 December 1978, Monday

Day	Time	t_{on}	t_{cyc}	t_R
53	0:56	9.12	58.87	0.1549
53	1:54	9.32	58.72	0.1587
53	2:53	9.23	56.63	0.1630
53	3:50	9.33	57.22	0.1631
53	4:47	9.25	56.33	0.1642
53	5:43	9.25	57.55	0.1607
53	6:41	9.27	38.80	0.2389
53	7:20	29.48	54.52	0.5407
53	8:14	5.85	47.97	0.1220
53	9: 2	9.25	148.85	0.0621
53	11:31	9.57	69.28	0.1381
53	12:40	9.42	67.15	0.1402
53	13:47	9.72	66.03	0.1471
53	14:54	9.27	64.18	0.1444
53	15:58	9.30	60.98	0.1525
53	16:59	9.30	60.67	0.1533
53	17:59	9.10	59.05	0.1541
53	18:58	9.37	52.13	0.1797
53	19:51	24.65	51.50	0.4786
53	20:42	4.48	34.25	0.1309
53	21:16	9.05	59.38	0.1524
53	22:16	9.25	60.55	0.1528
53	23:16	8.88	72.02	0.1234
54	0:28	9.42	54.57	0.1726
54	1:23	9.52	51.70	0.1841
54	2:15	9.50	51.22	0.1855
54	3: 6	9.88	51.12	0.1933

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APPENDIX E

LINEAR REGRESSION ANALYSIS COMPUTER CODES, AND RESULTS OF CYCLE-AVERAGED EFFICIENCY DATA EVALUATIONS

TABLE E-1

SUMMARY OF INDEX OF DETERMINATION FROM SIX FORMS OF LEAST-SQUARES CURVEFITTING TECHNIQUE USING TWO FORMS OF TIMING RATIO PARAMETERS

	Woodbine	Richard	Pond	Gravon	Stovepipe
$\eta = A + Bt_R$	.4915	.4004	.2276	.1643	.6212
$\eta = Ae^{Bt_R}$	.4617	.3980	.2079	.1524	.6676
$\eta = At_R^B$	.5938	.4463	.2992	.2491	.5598
$\eta = A + B/t_R$	.7048	.4400	.3430	.3051	.3432
$\eta = 1/(A + Bt_R)$	.4258	.3876	.1854	.1403	.7057
$\eta = t_R/(A + Bt_R)$	.6445	.4528	.3198	.2817	.4229
$\eta = A + Bt_{R1}$	.4436	.4033	.4143	.0461	.0067
$\eta = Ae^{Bt_{R1}}$	.4145	.3908	.3885	.0387	.0015
$\eta = At_{R1}^B$	.6494	.6003	.5568	.1046	.0002
$\eta = A + B/t_{R1}$	.8131	.6413	.6487	.1780	.0039
$\eta = 1/(A + Bt_{R1})$	.3808	.3752	.3581	.0319	.0000
$\eta = t_{R1}/(A + Bt_{R1})$	.7785	.6776	.6358	.1519	.0012

where:

$$(1) \quad t_R = \frac{t_{on_j}}{t_{on_j} + t_{off_j}} \qquad (2) \quad t_{R1} = \frac{t_{on_j}}{t_{off_{j-1}}}$$

TABLE E-2

RESULTS OF LINEAR REGRESSION ANALYSES OF THE CYCLE-AVERAGED THERMAL EFFICIENCY DATA FROM POND AVENUE AND GRAVON ROAD TEST SITES

Evaluation Number	Correlating Parameters	Pond		Gravon	
		r^2	σ	r^2	σ
1.	$1/t_{R1}$, $1/t_{on}$	.5531	3.26	.4974	3.51
2.	$1/t_R$, $1/t_{on}$	.3762	3.86	.3321	4.05
3.	$1/t_{R1}$	.4658	3.57	.3776	3.91
4.	$1/t_{on}$	.0566	4.74	.1636	4.53
5.	$1/t_{R1}$, $1/t_{on}$	.5950	1.58	.5909	2.24
6.	$1/t_R$, $1/t_{on}$	.8266	1.90	.3762	3.86
7.	$1/t_{R2}$, $1/t_{on}$	.8245	1.90	.6448	2.90
8.	$78\ t_R^{.1190}$	- .6254	3.16	.6364	2.74
9.	$84\ t_{R1}^{.1442}$	.6676	2.70	.3815	3.29

$$t_R = \frac{t_{on_j}}{t_{off_j} + t_{on_j}}$$

$$t_{R1} = \frac{t_{on_j}}{t_{off_{j-1}}}$$

$$t_{R2} = \frac{t_{on_j}}{t_{off_{j-1}} + t_{on_j}}$$

APPENDIX F

STATISTICAL EVALUATION OF INTEGRATED FURNACE FIELD TEST POLLUTANT EMISSIONS AND EFFICIENCY PERFORMANCE DATA

STATISTICAL EVALUATIONS AND RECOMMENDATIONS OF INTEGRATED RESIDENTIAL FURNACE FIELD TEST DATA

After an initial conference, the above data were analyzed. The following recommendations were made:

1. Equations 3, 4, or 6 of Table 11 be used to describe the Cycle-Averaged Efficiency Data.
2. Confidence intervals be used to describe the Overall Net Change in Efficiency and Measured Efficiency.
3. Outliers be eliminated from emission data by statistical procedures.
4. Statistical tests of the emission claims be presented.

Details of these recommendations are presented in Analyses 1 through 4. Supporting citations referenced at the end of each analysis are available for review upon request.

A. P. Lichtman
Statistical Analyst
QA Audits and Controls
Rockwell International

ANALYSIS 1

Reference: Table 11, "Results of the Single Parameter Linear Regression Analysis of Cycle-Averaged Efficiency Data Obtained from the Integrated Furnace Units in the 1977-1978 Field Test"

Recommendation: Equations 3, 4, or 6 of Table 11 used to describe the Cycle-Averaged Efficiency Data

Ninety-five percent confidence intervals for the correlation coefficients of the six sites and six equations were calculated using the following:

Formula 1:
$$\tanh\left(\operatorname{arctanh} R - \frac{1.96}{\sqrt{n-3}}\right) \leq \rho \leq \tanh\left(\operatorname{arctanh} R + \frac{1.96}{\sqrt{n-3}}\right)$$

There was 95% certainty that the correlation coefficient of the overall population of Cycle-Averaged Gross Thermal Efficiency measurements, which could have been taken, would be within the ranges listed in Table F-1. No limit approached zero. Thus, a relationship between Fractional On-Time and Cycle-Averaged Gross Thermal Efficiency existed with 95% surety.

Using the following equation, the correlation coefficients for Equations 4 and 6 were not significantly different at the 5% level. Equation 3 was different from Equations 4 and 6 only at the Woodbine site. Equations 4 and 6 were significantly different from Equations 1, 2, and 5 at the 95% confidence level at more than one site.

Formula 2:
$$W = \sum_{i+1}^{K} (n_i-3)\cdot(Z_i-\bar{Z})^2$$

where

$$Z_i = \operatorname{arctanh} R_i; \text{ and } \bar{Z} = \frac{\Sigma(n_i-3)Z_i}{\Sigma\,(n_i-3)}$$

W is compared to a $X^2_{\alpha,1}$. Equation 4 is the equation preferred over Equation 6, based on supplementary analyses on the parameters affecting cycle-averaged thermal efficiency of fired furnaces.

Citation: Franklin A. Graybill, *An Introduction to Linear Statistical Models*, Volume I (New York: McGraw-Hill, 1961), pp. 206-213

TABLE F-1

95% CONFIDENCE INTERVALS USING EQUATION 6

Site	n	Lower Limit	Upper Limit
Woodbine	2562	0.89	0.91
Richard	2008	0.78	0.82
Pond	508	0.77	0.83
Gravon	468	0.86	0.90
Stovepipe	506	0.88	0.92
Fissette	398	0.84	0.89

95% CONFIDENCE INTERVALS USING EQUATION 3

Site	n	Lower Limit	Upper Limit
Woodbine	2562	0.83	0.85
Richard	2008	0.78	0.82
Pond	508	0.74	0.81
Gravon	468	0.89	0.92
Stovepipe	506	0.89	0.92
Fissette	398	0.86	0.90

95% CONFIDENCE INTERVALS USING EQUATION 4

Site	n	Lower Limit	Upper Limit
Woodbine	2562	0.88	0.90
Richard	2008	0.81	0.83
Pond	508	0.77	0.83
Gravon	468	0.87	0.91
Stovepipe	506	0.89	0.92
Fissette	398	0.84	0.89

ANALYSIS 2

Reference: Table 14, "Effect of Integrated Furnace on Fuel Oil Consumption"

Recommendation: Confidence intervals be used to describe the Overall Net Change in Fuel Consumption and Measured Cycle-Average Efficiency

Since random error is part of any distribution of data, confidence intervals should be used to describe essential conclusions. The confidence interval for a mean of a normal distribution is given by:

Formula: $\bar{X} \pm t_{\alpha/2,(n-1)} \cdot s/\sqrt{n}$

where

$$\bar{X} = 1 - \frac{\bar{W}_{after}}{\bar{W}_{before}}$$

s = Pooled standard deviation of six standard deviations, each based on the same number of readings

One has $(1-\alpha) \cdot 100$ % confidence that the mean of the population of all possible data points, μ, is in the interval whose bounds are determined by this formula. Thus, it could be stated that there is 95% confidence that the true mean net change in fuel consumption was at least -8.75 or as much as -24.70 (see Table F-2).

Citation: Bernard Ostle, Statistics in Research, Second Edition (Ames, Iowa: Iowa State University Press, 1963), pp. 90-92

TABLE F-2

95% CONFIDENCE INTERVALS FOR THE MEAN

	Lower	Mean	Upper
New Change in Fuel Consumption	-24.70	-16.72	-8.75
Measured Cycle-Averaged Efficiency	66.66	75.31	83.96

ANALYSIS 3

Reference: "Test Pollutant Emissions Summary for the Boston-Area Installations" and "1977-78 Integrated Furnace Field Test Pollutant Emissions Summary for the Albany-Area Installations"

Recommendation: Outliers be eliminated from emission data by statistical procedures

Since statements concerning the overall quality of pollutants were of concern, those data points which were statistically different from the remaining points were eliminated. These "outliers" were determined by the Thompson Tau Technique.

Formula: X_i is an outlier if $X_i - \overline{X} > S\tau$

Table F-3 shows the mean and standard deviation, before and after elimination of the "outlier," and the "outlier" in question.

Citation: William R. Thompson, "On a Criterion for the Rejection of Observations and the Distribution of the Ratio of Deviation to Sample Standard Deviation," from Annals of Mathematical Statistics, Vol. 6 (1935)

TABLE F-3

STOICHIOMETRIC RATIO

Site	Mean, $\overline{X}$	Standard Deviation, s	"Outlier"
Woodbine	1.23 (1.23)	.02 (.01)	1.27
Richard	1.26 (1.23)	.08 (.02)	1.45
Pond	1.23	.05	-
Gravon	1.26	.03	-
Stovepipe	1.22 (1.21)	.04 (.02)	1.31
Fissette	1.20	.02	-

CO

Site	Mean, $\overline{X}$	Standard Deviation, s	"Outlier"
Woodbine	.70	.20	-
Richard	1.47 (.96)	1.73 (.82)	5.60
Pond	.55	.13	-
Gravon	.57	.11	-
Stovepipe	.99 (.84)	.55 (.31)	2.23
Fissette	1.05 (.90)	.53 (.31)	2.24

NO

Site	Mean, $\overline{X}$	Standard Deviation, s	"Outlier"
Woodbine	.688	.162	-
Richard	.536	.107	-
Pond	.584	.028	-
Gravon	.572	.060	-
Stovepipe	.509 (.534)	.103 (.076)	.310
Fissette	.535 (.523)	.049 (.033)	.637

TABLE F-3
(Continued)

UHC

Site	Mean, $\overline{X}$	Standard Deviation, s	"Outlier"
Woodbine	.064	.025	-
Richard	.042	.015	-
Pond	.039	.019	-
Gravon	.045 (.040)	.016 (.009)	.082
Stovepipe	.036 (.026)	.030 (.011)	.110
Fissette	.090 (.052)	.117 (.010)	.400

SMOKE

Site	Mean, $\overline{X}$	Standard Deviation, s	"Outlier"
Woodbine	1.1 (.6)	1.5 (.8)	4.5
Richard	.2	.2	-
Pond	.4 (.2)	.7 (.2)	2.0
Gravon	.1 (.0)	.3 (.0)	1.0
Stovepipe	.1 (.01)	.1 (.04)	0.4
Fissette	.0 (.0)	.03 (.0)	0.1

( ) Means and Standard Deviations after elimination of "outlier"

ANALYSIS 4

Reference: Emission data conclusions

Recommendation: Statistical tests of the emission claims be presented

In all places in which the claim of lowering the NO level or holding the level on other emissions was made, a statistical test known as a one-tail t-test should be used. There were two hypotheses in the test, the null hypothesis that the true mean, μ, was less than or equal to a specific quantity, μ_0, and the alternate hypothesis that the true mean was greater than the quantity. The t was calculated using the following:

Formula: $t = \sqrt{n}\,(\bar{X} - \mu_0)/s$

The null hypothesis was rejected at the α significance level if $t \geq t_{\alpha,(n-1)}$. The rejection limit (t_α) for the 5% significance level for the given data sets of 10 (monthly) readings is 1.833. Thus, if the "t" values calculated for all six sites' data are less than this limit, the null hypothesis is not rejected and, therefore, accepted as statistically true. The 5% significance level represents the probability of the conclusion not being true.

All of the tests made, with the exception of the CO data from the Stovepipe and Fissette sites, were based on the data with outliers removed. Calculated t's are presented in Tables F-4a to F-4e. Specific conclusions for each pollutant follow each table.

Using the 5% significance level, the mean of the stoichiometric ratios did not exceed 1.25. The mean of the CO readings did not exceed 0.70. The mean of the NO readings did not exceed 0.590. The mean of the UHC readings did not exceed 0.050. And the mean of the smoke readings did not exceed 0.1.

Citation: Bernard Ostle, Statistics in Research, Second Edition (Ames, Iowa: Iowa State University Press, 1963), pp. 113-114

TABLE F-4a

STOICHIOMETRIC RATIO

Site	$\overline{X}$	s	t for $\mu_o = 1.2$	t for $\mu_o = 1.25$
Woodbine	1.23	.01	8.49**	-5.66
Richard	1.23	.02	4.24*	-2.83
Pond	1.23	.05	1.80	-1.20
Gravon	1.26	.03	6.00**	1.00
Stovepipe	1.21	.02	1.41	-5.66
Fissette	1.20	.02	0.00	-7.50

Null Hypothesis: $\mu \leq 1.20$

Alternate Hypothesis: $\mu > 1.20$

Formula: $t = \sqrt{n}\,(\overline{X} - 1.20)/s$

Conclusions: *significantly greater than 1.20 at $\alpha = .005$
**significantly greater than 1.20 at $\alpha = .0005$

In three sites, the mean of stoichiometric ratios was significantly greater than the proposed 1.20.

Null Hypothesis: $\mu \leq 1.25$

Alternate Hypothesis: $\mu > 1.25$

Formula: $t = \sqrt{n}\,(\overline{X} - 1.25)/s$

Conclusion: The null hypothesis could not be rejected at the 5% significance level. All six means were accepted to be less than or equal to 1.25 at the 5% level.

TABLE F-4b

CO

Site	$\overline{X}$	s	t for $\mu_o = .6$	t for $\mu_o = .7$
Woodbine	.70	.20	1.50	0
Richard	.96	.82	1.24	.90
Pond	.55	.13	-1.15	-3.46
Gravon	.57	.11	- .82	-3.55
Stovepipe	.84	.31	2.19	1.28
Fissette	.90	.31	2.74	1.82

The occasionally high CO readings noted at Stovepipe and Fissette were confirmed readings of real conditions; thus, the exclusion of outlier points is not applicable and the evaluation was extended to include the previously excluded data.

Site	$\overline{X}$	s	t for $\mu_o = .6$	t for $\mu_o = .7$	t for $\mu_o = .73$
Stovepipe	.99	.55	2.13*	1.58	1.42
Fissette	1.05	.53	2.55**	1.98*	1.81

Null Hypothesis: $\mu \leq .60$

Alternate Hypothesis: $\mu > .60$

Formula: $t = \sqrt{n}\,(\overline{X} - .6)/s$

Conclusions: *significantly greater than .60 at $\alpha = .05$
**significantly greater than .60 at $\alpha = .025$

In two sites, the mean of CO measurements was significantly greater than the proposed .60.

Null Hypothesis: $\mu \leq .70$

Alternate Hypothesis: $\mu > .70$

Formula: $t = \sqrt{n}\,(\overline{X} - .7)/s$

Conclusion: *significantly greater than .70 at $\alpha = .05$. In one site, the mean of the CO measurements was significantly greater than .70.

Null Hypothesis: $\mu \leq .73$

Alternate Hypothesis: $\mu > .73$

Formula: $t = \sqrt{n}\,(\overline{X} - .73)/S$

Conclusion: The null hypothesis could not be rejected at the 5% significance level. All six means were accepted to be less than or equal to .70 at the 5% level.

TABLE F-4c

NO

Site	$\overline{X}$	s	t for $\mu_o = 1.800$	t for $\mu_o = .650$	t for $\mu_o = .590$
Woodbine	.688	.162	- 20.623	.704	1.815
Richard	.536	.107	- 35.366	- 3.196	-1.514
Pond	.584	.028	-130.998	- 7.071	- .643
Gravon	.572	.060	- 61.471	- 3.900	- .900
Stovepipe	.534	.076	- 47.344	- 4.317	-2.084
Fissette	.523	.033	-109.602	-10.885	-5.743

Null Hypothesis: $\mu \leq 1.800$

Alternate Hypothesis: $\mu > 1.800$

Formula: $t = \sqrt{n}\,(\overline{X} - 1.800)/s$

Conclusion: The null hypothesis could not be rejected at the 5% significance level. All six means were accepted to be less than or equal to 1.800 at the 5% level.

Null Hypothesis: $\mu \leq .650$

Alternate Hypothesis: $\mu > .650$

Formula: $t = \sqrt{n}\,(\overline{X} - .650)/s$

Conclusion: The null hypothesis could not be rejected at the 5% significance level. All six means were accepted to be less than or equal to .650 at the 5% level.

Null Hypothesis: $\mu \leq .590$

Alternate Hypothesis: $\mu > .590$

Formula: $t = \sqrt{n}\,(\overline{X} - .590)/s$

Conclusion: The null hypothesis could not be rejected at the 5% significance level. All six means were accepted to be less than or equal to .590 at the 5% level.

TABLE F-4d

UHC

Site	$\overline{X}$	s	t for μ_0 = .070	t for μ_0 = .050
Woodbine	.064	.025	- .668	1.680
Richard	.042	.015	- 5.520	-1.600
Pond	.039	.019	- 4.971	-1.737
Gravon	.040	.009	- 9.067	-3.143
Stovepipe	.026	.011	-11.286	-6.171
Fissette	.052	.010	- 5.096	.566

As in the case of the CO emissions, the high UHC emissions occasionally noted at Stovepipe and Fissette sites were confirmed readings not subject to exclusion as outliers. The reevaluation of the Stovepipe and Fissette data is shown below.

Site	$\overline{X}$	s	t for μ_0 = .070	t for μ_0 = .050
Stovepipe	.036	.030	-3.400	-1.400
Fissette	.090	.117	.513	1.026

Null Hypothesis: $\mu \leq .070$

Alternate Hypothesis: $\mu > .070$

Formula: $t = \sqrt{n}\,(\overline{X} - .070)/s$

Conclusions: The null hypothesis could not be rejected at the 5% significance level. Both means were accepted to be less than or equal to .070 at the 5% significance level.

Null Hypothesis: $\mu \leq .050$

Alternate Hypothesis: $\mu > .050$

Formula: $t = \sqrt{n}\,(\overline{X} - .050)/s$

Conclusion: The null hypothesis could not be rejected at the 5% significance level. Both means were accepted to be less than or equal to .050 at the 5% significance level.

TABLE F-4e

SMOKE

Site	$\overline{X}$	s	t for $\mu_o = 1.3$	t for $\mu_o = 1.0$	t for $\mu_o = 0.1$
Woodbine	.6	.8	- 2.32	- 1.41	1.77
Richard	.2	.2	- 13.20	-12.00	1.50
Pond	.2	.2	- 14.76	-11.31	1.41
Gravon	.0	.0	-	-	-
Stovepipe	.01	.04	-103.00	-70.00	-6.36
Fissette	.0	.0	-	-	-

Null Hypothesis: $\mu \leq 1.3$

Alternate Hypothesis: $\mu > 1.3$

Formula: $\sqrt{n}\,(\overline{X} - 1.3)/s$

Conclusion: The null hypothesis could not be rejected at the 5% significance level. All six means were accepted to be less than or equal to 1.3 at the 5% level.

Null Hypothesis: $\mu \leq 1.0$

Alternate Hypothesis: $\mu > 1.0$

Formula: $\sqrt{n}\,(\overline{X} - 1.0)/s$

Conclusion: The null hypothesis could not be rejected at the 5% significance level. All six means were accepted to be less than or equal to 1.0 at the 5% level.

Null Hypothesis: $\mu \leq 0.1$

Alternate Hypothesis: $\mu > 0.1$

Formula: $\sqrt{n}\,(\overline{X} - 0.1)/s$

Conclusion: The null hypothesis could not be rejected at the 5% significance level. All six means were accepted to be less than or equal to 0.1 at the 5% level.